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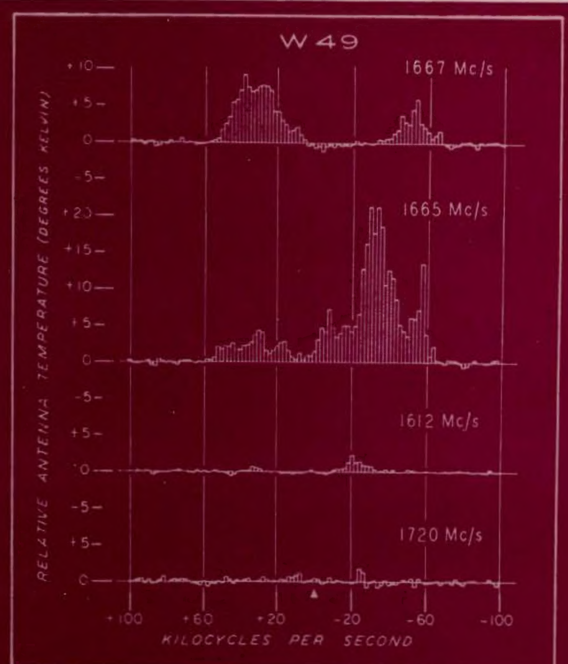
SYMPOSIUM No. 31

RADIO ASTRONOMY AND THE GALACTIC SYSTEM

Edited by Hugo van WOERDEN



INTERNATIONAL ASTRONOMICAL UNION

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van WOERDEN

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ACADEMIC PRESS

The IAU/URSI Symposium on Radio Astronomy and the Galactic System, held at Noordwijk (Netherlands) in August 1966, brought together some 90 experts—optical and radio astronomers, cosmic-ray physicists and astrophysicists, theoreticians and observers—in an effort to analyze and understand the wealth of new information on our Galaxy obtained by radio-astronomical and other methods. Subjects discussed ranged from the internal motions and physical processes in interstellar clouds to the origin of the Galaxy. They included such controversial issues as the enigmatic behaviour of OH molecules and the presence or absence of a halo of relativistic electrons around the Galaxy. Other highlights were the success of gravitational theories of galactic spiral structure, the discussion of the large amounts of high-velocity gas which may be falling into the Galaxy from intergalactic space, and the first report of identification of the strongest cosmic X-ray source, Sco X-1, with an optical object.

Le Symposium IAU–URSI sur la Radioastronomie et le Système Galactique, qui s'est tenu à Noordwijk (Pays-Bas) au mois d'août 1966, a réuni environ 90 experts (des spécialistes de l'astronomie optique, de la radioastronomie, des rayons cosmiques, des théoriciens aussi bien que des observateurs) dans un effort pour analyser et comprendre la richesse des informations que les méthodes radioastronomiques, et autres permettent d'accumuler au sujet de la Galaxie. La discussion a couvert des sujets aussi divers que l'étude des mouvements et des processus physiques à l'intérieur des nuages interstellaires ou celle de l'origine de la Galaxie. Les controverses se sont développées sur le comportement étrange des molécules OH et sur la présence (ou l'absence) d'un halo d'électrons relativistes autour de la Galaxie. D'autres foyers d'intérêt furent le succès des théories gravitationnelles de la structure spirale, la discussion des grandes quantités de gaz à grande vitesse qui peuvent tomber dans la Galaxie à partir du milieu intergalactique, et la première information sur l'identification de la source cosmique de rayons X la plus forte, Sco X-1, avec un objet observable dans le domaine optique.

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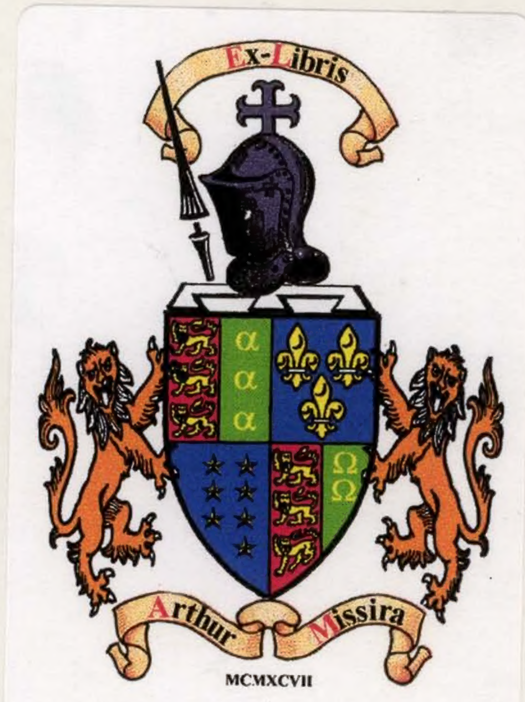
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SYMPOSIUM No. 31

ORGANIZED BY THE IAU IN CO-OPERATION WITH URSI

HELD AT NOORDWIJK, THE NETHERLANDS,

25 AUGUST – 1 SEPTEMBER 1966

RADIO ASTRONOMY AND THE GALACTIC SYSTEM

EDITED BY

HUGO VAN WOERDEN

(*Sterrenkundig Laboratorium 'Kapteyn', Groningen*)

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III E. *X-Rays in the Galaxy*
(Chairmen: H. Alfvén and L. Biermann)

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PREFACE

The Symposium on Radio Astronomy and the Galactic System, held in Hotel De Baak in Noordwijk from 25 August to 1 September 1966, was organized jointly by the International Astronomical Union and the International Scientific Radio Union. The Scientific Organizing Committee consisted of J. H. Oort (President), A. Blaauw, G. R. Burbidge, R. Coutrez, F. J. Kerr, M. Ryle, I. S. Šklovskij, and L. Woltjer. The Symposium was attended by 87 invited participants, nearly all of which contributed actively to the liveliness of the meetings.

The backbone of the Symposium consisted of 18 introductory reports, which were intended as broad reviews of recent and current investigations on the various subjects covered by the programme. The essence of these reviews and of a number of short communications on related topics is printed in this volume. It is, alas, impossible to present in print that other invaluable aspect of an international symposium of experts, which is in the personal relations and discussions among the participants outside the scheduled meetings. The editors have, however, taken considerable pains to report the discussions which took place during the meetings.

I wish to record the indebtedness of the Scientific Organizing Committee to several astronomers for valuable personal advice concerning the introductory reports, and to the Minister of Education and Science of the Netherlands, the Stichting Het Leids Kerkhoven Bosscha Fonds, and the Philips Company at Eindhoven for their liberal support of facilities contributing to intensify the contact between the participants. IAU and URSI gave subsidies towards travel and editorial expenses. Further support was given by the Dienst der Zuiderzeewerken (Den Haag) and by the Universities of Groningen and Leiden. We also want to express our gratitude for the efficient way in which Dr. E. Raimond, Dr. H. van Woerden, and a number of young astronomers of the Groningen and Leiden Observatories have dealt with all aspects of the local organization. We are likewise much indebted to the management of Hotel De Baak for their constant cooperation.

The outside curriculum comprised, among other items, an excursion through the canals of Amsterdam, with a visit to Holshuysen and Stoeltie, diamond cutters, a concert of 14th-century chamber music by the Ensemble 'Syntagma Musicum' in the Municipal Museum 'De Lakenhal' at Leiden, a boat trip with a visit to dyke construction in the former Zuiderzee and to the most recently reclaimed polder of Oostelijk Flevoland, and a visit to the Kröller-Müller Museum near Arnhem.

J. H. Oort

EDITOR'S FOREWORD

Following the Symposium programme, this volume consists of three parts, subdivided into a total of sixteen chapters (sections), as shown in the Table of Contents. Each chapter opens with one or two Introductory Reports, usually followed by a few Short Communications—some of them invited by the Organizing Committee, others contributed spontaneously as a scheduled paper or as part of the discussions. The distinction between the last two categories being somewhat vague, I have indexed both papers and discussion remarks, to facilitate reference to these contributions.

The original programme comprised a section on the Galactic Halo. At the request of the invited reviewer, no formal report on the halo was presented, but the subject was incorporated in Sections III A (Distribution and Spectrum of the Non-Thermal Radiation; the Galactic Halo) and III D (Cosmic Rays in the Galaxy), where it led to vivid discussions.

In some places, where this appeared to offer a logical advantage, I have slightly changed the order of papers from that in the actual programme. Discussion periods were held partly after individual communications, partly after several related papers. Here again, I have taken the liberty to rearrange discussion remarks so as to enhance their coherence without violating the original train of thinking.

The discussion contributions were edited from sheets filled in by participants during the Symposium. However, all the oral presentations and discussions were also tape-recorded. These recordings have helped to complete our discussion records, and in particular to stimulate eight authors of Introductory Reports whose manuscripts were delayed too long. Dr. Charles R. Tolbert was in charge of these arrangements and has succeeded in making available a complete and reliable record of what was said during the Symposium. But for his efficient help, this volume would have been far less comprehensive and balanced than it is now; I thank him most cordially for his share in the work.

Under each chapter title, the reader finds an epigraph representing an (almost) verbal quotation from the tape recordings. We hope these remarks will transmit to the reader some of the atmosphere of the Symposium, which has been so important to its success and so stimulating to participants.

In this and in other editorial jobs, I have had the assistance of Charles Tolbert and Harm J. Habing. Our secretaries (Miss I. de Boer, Mrs. L. Freeve, Mrs. H. de Graaf, Miss T. E. Stuit and Mrs. S. M. M. van Woerden) have done a great amount of work, under high pressure and in a perfect fashion. Many of the figures were ably redrawn by Mr. J. J. Dekker.

I further wish to thank Dr. J.-C. Pecker, General Secretary of the IAU, and Mlle G. Drouin of Meudon for their efforts in preparing this volume for the press, and in having it published rapidly after serious delays in the editorial work. I have attempted to follow the new IAU Style Book (*Trans. IAU*, XII C) as closely as possible. Galactic coordinates are on the new (l^{II}, b^{II}) system unless otherwise stated.

A number of illustrations in this volume have been reproduced from earlier publications, as indicated by credits in the figure captions. I thank the publishers of the various journals for their courtesy.

During the Symposium, Professor Strömgren made the following announcement, on behalf of Columbia University:

"The 1966 Vetlesen Prize will be awarded to Professor Oort. The Prize consists of the Vetlesen gold medal and an amount of $25 000. The prize was established at Columbia University in 1960 by the Vetlesen Foundation. The award is given every two years, for achievement in the sciences of the Earth and the Universe. This is the first time that the Prize is given to an astronomer, and we all share in the joy that Professor Oort was the first to receive this award."

Sterrenkundig Laboratorium 'Kapteyn',
Groningen, Nederland

HUGO VAN WOERDEN

May 1967

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From Groningen: T. S. van Albada, I. Fejes, H. J. Habing, Dr. D. Sher.

Part I

INTERSTELLAR CLOUDS

'Never take the size or mass of a cloud as the starting point or end point of a scientific argument.'

H. C. van de Hulst, in the Discussion (Paper 23)

I.A.U. Symposium no. 31, 1967

Chapter I A

Structure and Motions in the Interstellar Medium

CHAIRMAN: B. Strömgren

(Institute for Advanced Study, Princeton, New Jersey, U.S.A.)

'I quote from Spitzer's Compendium chapter, which is in press since 1960.'

H. van Woerden, in Paper 1

1. STRUCTURE AND MOTIONS IN THE INTERSTELLAR MEDIUM

(Introductory Report)

HUGO VAN WOERDEN

(Sterrenkundig Laboratorium 'Kapteyn,' Groningen, Nederland

and

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ABSTRACT

This review summarizes information obtained from studies of dark matter, of optical interstellar absorption lines, and of the 21-cm line observed in absorption and in emission.

Great improvements in the velocity resolution of interstellar lines (Section 4) are making possible a detailed analysis of their component structure, and determination of the internal motions in the clouds. The 21-cm absorption spectra of strong radio sources (Section 5) have yielded statistics of the optical depths and the internal velocity dispersions of absorbing clouds. Studies of the 21-cm line in emission (Section 6) supply a wealth of data on internal motions in the clouds. Comparisons of Gaussian component parameters at neighbouring positions allow delineation of cloud boundaries on the sky, but estimates of size and mass depend on (usually unknown) distance. The Green Bank telescope has revealed the existence of 'cloudlets' containing a few solar masses within a volume of about 5 pc diameter.

Structural details in the interstellar medium show a wide variety of size, density and mass. Recent studies tend to emphasize the smaller and thinner structures. The external cloud motions are best approximated by an exponential velocity distribution, with a root-mean-square velocity of 7 km/sec in one coordinate. Internal motions within the clouds probably have Gaussian distributions, with velocity dispersions ranging from 0·6 to possibly 7 km/sec; part of these may be due to non-thermal mass motions.

1. INTRODUCTION

My original assignment was to review 'observational data on the structure and motions of interstellar clouds'. There is a long-standing controversy about the interstellar-cloud concept, and several authors have emphasized that this vague concept can only be defined in terms of a particular set of observations or a specific type of investigation. Among the structural details of the interstellar medium listed by Van de Hulst (1958, Table IV), the sizes of objects sometimes called 'interstellar clouds' range at least from 0·1 pc (globules) to 100 pc (condensations in spiral arms), a factor 1000. In these circumstances I have preferred to avoid the term 'clouds' in my title, although it will often turn up in the text. We shall see what structures and motions one observes in the interstellar medium—and forget about the terminology.

The subject is so large that a comprehensive summary would far surpass the scope of this Symposium paper. As supplementary material, I recommend the recent reviews by Dieter and Goss (1966), Kerr (1967*a*, 1967*b*), Münch (1967), and Spitzer (1967).

2. SOURCES OF INFORMATION

Our main sources of information on the interstellar medium are in the optical and radio spectra. In either of these, both continuum and line spectrum are important.

The optical continuum carries information on extinction, reddening, polarization, scattering, and reflection—all by solid particles. We shall not discuss the physics of these particles, but we shall briefly touch upon two features of their, highly irregular, space distribution: the dark clouds and the reflection nebulae (Section 3).

An optical line spectrum, together with a weak continuum, is emitted by the diffuse emission nebulae, called H II regions because the hydrogen in them is predominantly ionized. These regions are the subject of Paper 36 (Mrs Burbidge) and other communications in chapter IIC of this Symposium volume, and their physics is also treated by Kahn in Paper 15. We shall here refrain from discussion of these objects.

Optical absorption lines, produced by various interstellar atoms and molecules, are observed in the spectra of early-type stars. These lines furnish valuable data on the distribution *and* motions of atoms and molecules in interstellar space, as well as on the chemical composition and physical state of the interstellar gas. We review the data on distribution and motions in Section 4. The weakness of this source of information is in its restriction to a tiny fraction of interstellar space: later-type stars have too many lines in their own spectra; early-type stars are rare, and they are concentrated in small areas of sky, leaving many directions of line of sight uninvestigated.

At radio wavelengths, again both a continuum and a line spectrum are emitted by H II regions; Mezger (Paper 38) and Mrs Dieter (Paper 39) report on studies of the recombination lines. The 18-cm lines absorbed and emitted by OH molecules are the subject of chapter IB; as noted by Robinson in his review (Paper 7), the information carried by these lines is so far highly confusing.

Finally, there is the 21-cm line of neutral hydrogen. It is observable in emission anywhere in the sky, and it tells us about distribution and motions of the most abundant constituent of the interstellar gas. Its disadvantage is in limited angular resolution. In absorption against strong radio sources, the 21-cm line allows studies combining high

angular *and* velocity resolutions with a good signal-to-noise ratio. We discuss the information obtained from 21-cm absorption and emission in Sections 5 and 6.

In Section 7 we shall make direct comparisons of the observations of 21-cm emission and optical absorption lines. We conclude with summaries of the results concerning the structure and motions in the interstellar medium derived by various methods.

3. DARK CLOUDS AND REFLECTION NEBULAE*

Several catalogues of objects recognized as assemblies of solid particles have appeared recently. Mrs Lynds (1962) published a catalogue of dark nebulae compiled from the blue and red Palomar Sky Survey prints. The catalogue is accompanied by statistics of angular sizes and opacities. The dark clouds are found predominantly along Gould's Belt.

Dorschner and Gürtler (1963, 1965) and Van den Bergh (1966) have published catalogues of reflection nebulae based on the Sky Survey, and made statistics of these objects. Van den Bergh lists 13 associations of reflection nebulae. These nebulae, too, tend to fall in Gould's Belt. Dorschner (1967) has determined diameters.

A series of papers on interstellar absorption has recently come from Heidelberg-Königstuhl. Neckel (1966) determines the space distribution of absorbing matter from measures of colour-excesses of stars and galactic clusters. He finds large dust clouds, 100 to 1000 pc in size. The average thickness of the dust layer is about 40 pc. Scheffler (1966, 1967*a*, 1967*b*) discusses the distribution of the sizes of colour excess and derives a cloud model allowing two types of clouds: small ones (visual absorption 0·25 magnitudes; diameter 3 pc; line density 5 kpc^{-1}) and large ones (absorption 2 magnitudes; diameter 25 pc; line density 0·5 kpc^{-1}). The masses of both types are 25 $\odot$ and 15 000 $\odot$, respectively. Scheffler (1967*b*) further determines the mass spectrum of clouds of various sizes. We shall use his cloud model, together with those obtained by others, in Section 8.

4. INTERSTELLAR ABSORPTION LINES

A few dozen sharp interstellar lines are now known; for a recent review see Herbig (1963). (Our understanding of the diffuse interstellar bands is summarized by Herbig in Paper 13.) These lines are of great importance for our knowledge of composition and physical state of the interstellar gas. However, most of them are weak and observed in only a few stars. The only lines strong enough to allow detailed investigation in a large number of stars are the Ca II doublet (H, K) at 3968 and 3934Å, and the Na I doublet (D_1, D_2) at 5896 and 5890Å.

The first study with adequate velocity resolution was that by Adams (1941, 1943); following the first discovery by Beals (1936) of a splitting in the interstellar H and K lines, he found that in many stars these lines showed two or more discrete components. These components rapidly obtained the name 'clouds', although there neither was direct evidence for a relationship to the known dark clouds, nor an immediate delineation of the cloud boundaries on the sky was available. Nevertheless, the term appears justified. Some people maintain that what one sees is 'currents' of gas rather than clouds; but with an average density of 1 atom cm^{-3} near the galactic plane, as determined later,

*This section was added after the Symposium.

the mean free path of 10^{16} cm is many orders shorter than the line of sight; thus, the currents must be either separated in space or stop each other in a few hundred years. Moreover, Adams (1949) and later Schlüter *et al.* (1953) determined groups of stars, sometimes several degrees across, in which the structure of the K lines was closely similar. Recently Münch and Unsöld (1962) found, in the Hercules-Ophiuchus region, a nearby cloud with dimensions of the order of 1 pc.

The bulk of our information on the interstellar absorption lines is still due to Adams (1949), who listed measured velocities and estimated intensities for the components of the Ca^+ K line in 300 early-type stars. The velocity resolution of these observations, estimated by Blaauw (1952) from statistics of velocity differences, is between 9 and 18 km/sec. From the same data, Blaauw found that the cloud velocities, V_0, follow the exponential distribution:

$$f(V_0) = (2\eta)^{-1} \exp\{ - | V_0 - \bar{V}_0 | / \eta\} \quad , \tag{1}$$

with $\eta = 5 \pm 1$ km/sec in the solar neighbourhood ($r < 300$ pc) and $\eta = 8$ km/sec at larger distances. The number of clouds per kpc would be about 10. Takakubo (1958) came to similar conclusions.

The velocity distribution $f(V_0)$ is that of cloud velocities V_0 with respect to their group average, $\bar{V}_0$. Spitzer and Skumanich (1952) attempted to determine the velocity distribution of atoms *within* a cloud. They suggested that this distribution is Gaussian:

$$\Psi(V) = (2\pi\sigma^2)^{-1/2} \exp\{ - (V - V_0)^2/2\sigma^2\} \quad , \tag{2}$$

with σ between 2 and 5 km/sec; but this result was based on only two spectra, and uncertain because of considerable corrections for instrumental broadening.

Münch (1957, 1965) applied the study of interstellar absorption lines to problems of galactic structure. In his analysis of gas in the Orion and Perseus Arms, he concluded from the observed doublet ratios again to exponential velocity distributions (1), with values of η ranging between 3 and 6 km/sec.

We shall here refrain from discussion of the properties of gas clouds away from the galactic plane, derived by Münch and Zirin (1961) from spectra of stars at high galactic latitudes, and leave these for the chapter on high-velocity gas (see Oort, Paper 46, Section 1*f*).

Strömgren (1948) has determined cloud sizes and densities from line strengths measured by Adams and Dunham; this work has been summarized by Van de Hulst (1958, p. 920).

The work reviewed so far was all done with velocity resolutions of 10 to 20 km/sec. Since 1958, higher resolutions have become increasingly available. In the 100-inch coudé spectrograph at Mount Wilson, a grating with twice higher angular dispersion and the use of less grainy plates brought the velocity resolution to 3 km/sec. Following early work by Oke (1959) and Münch, I have in 1962–64 collected spectra with resolutions of 3 to 5 km/sec for about 100 stars. Figure 1 illustrates the resolution achieved. Further examples are given in Figure 12. In the Orion region, these high-resolution spectra are available for some 40 positions, whose angular separations range from 2$''$.5 to several degrees, so that detection of a wide size range of structural detail should be possible.

Two important results of the gain in velocity resolution are apparent from preliminary

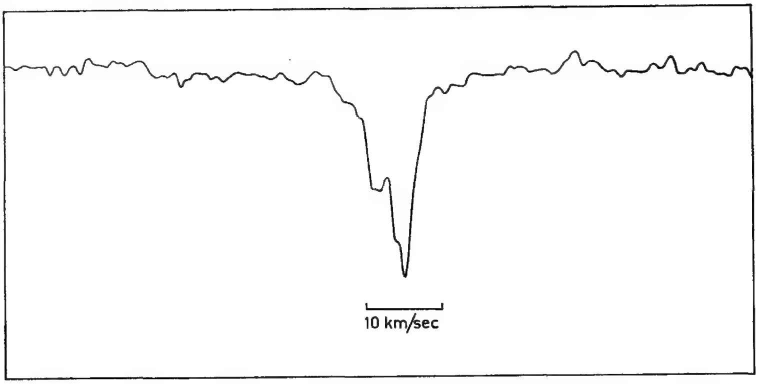

FIG. 1. Microphotometer tracing of the Ca^+ K line in the spectrum of υ Orionis, taken at the 100-inch coudé with 1·1 Å/mm dispersion. The velocity resolution of the spectrum is of the order of 3 km/sec.

analysis of this extensive material. The number of components seen in the spectra is about double that listed by Adams (1949). And the internal motions in the 'clouds' can now be much better derived from the detailed shape of a K-line component. The narrowest components detected have velocity dispersions (corrected for instrumental broadening!) of about 1 km/sec.

At Okayama (Japan), Takakubo (1963*b*) has used a similar velocity resolution, but this setup is not permanently available.

Much higher resolutions have recently been obtained with quite new techniques. Livingston and Lynds (1964) have used the Kitt Peak solar telescope with image intensifier tubes, reaching velocity resolutions of 0·5 km/sec in quite reasonable exposure times. From a comparison of their published spectra with my own plates, I conclude that further structure in the interstellar lines is revealed at least for some of the stars. – Similar resolutions (0·5 to 1 km/sec) at short exposure times are also achieved with Fabry-Pérot interferometers. Hobbs (1965, 1966) at Lick, and Vaughan and Münch (1966; see also Münch and Vaughan 1966) at Mount Wilson have observed several tens of stars with these techniques; reports so far are not very specific, but it is clear that the method holds great promise.

Finally, I must mention that new possibilities are being opened and problems posed by the far-ultraviolet. Morton and Spitzer (1966) have detected interstellar lines of O I, S I, Al II, and possibly C II at wavelengths between 1300 and 1700 Å in the spectra of δ and π Sco obtained with a rocket. High-resolution observations of these more abundant atoms from astronomical satellites would considerably enhance our knowledge of the interstellar medium. Morton (1966, 1967) finds, from the interstellar Lyman-α line (1216 Å) in the spectra of δ and ζ Ori, a surface density of neutral hydrogren of the order of 10^{20} atoms cm^{-2}, while the 21-cm emission yields 10^{21} atoms. The cause of this discrepancy is unclear, but it must be important to our understanding of the structure and/or physical state of the gas in the Orion Association.

5. THE 21-CM LINE IN ABSORPTION

At the Paris Symposium, Muller (1959) reported detailed measurements, with 1 km/sec bandwidth, of the absorption spectra of four strong radio sources: Cas A, Tau A, Cyg A, and Ori A. He resolved* the profiles into a total of 20 Gaussian components, with velocity dispersions σ ranging from 1·0 to 2·6 km/sec. For the five strongest—thus best determined—components, with central optical depths τ_0 between 1·4 and 4, the dispersions averaged 1·8 km/sec.

In recent years, Soviet astronomers have published studies of 21-cm absorption in the spectra of the galactic-centre source (Ryžkova *et al.* 1963, 1964, Egorova 1963, 1964) and of several other sources (Bystrova *et al.* 1964*a*, 1964*b*, 1965). In these studies and in that of the source W49 by Akabane and Kerr (1965), the bandwidths were too large (17 and 8 km/sec) for detailed conclusions of the type drawn by Muller.

Narrow-band studies have been made at the Owens Valley Radio Observatory, with the twin 90-foot (27-m) interferometer at baselines ranging from 144 to 578 wavelengths. The interferometric method has the advantage of giving information about the brightness distribution in the hydrogen line across the source, thus supplying the angular scale of absorption features. Clark *et al.* (1962) investigated the spectra of twelve sources, with a bandwidth (velocity resolution) of about 1·3 km/sec. Most spectra contain one or more deep absorption components ($\tau_0 > 0·5$). For these (rather) opaque clouds, Clark *et al.* derived the following tentative parameters: line density $k = 1$ kpc^{-1}, diameter $2a = 13$ pc, hydrogen density $n_H = 20$ cm^{-3}, mass $M = 1000 \odot$.

The spectra of five strong sources: Cas A, Tau A, Sgr A, Ori A, and M17 (Omega Nebula), have been examined in much more detail by Clark (1965), again with 1·3 km/sec bandwidth. Where necessary, he applied a crude bandwidth correction to the profiles. Analysis into Gaussian components (cf. Section 6) supplied radial velocities V, central optical depths τ_0, velocity dispersions σ, and hydrogen surface densities N_H (with an assumed gas temperature, $T_g = 100$ °K); the angular scale then yielded density n_H and mass M, with the distance to the cloud derived from its velocity via differential galactic rotation. Figure 2 shows the distribution of central optical depths τ_0. The exponential distribution $n = n_0 \exp(-1·3\, \tau_0)$ approximates the data closely. Figure 3 illustrates the distribution of velocity dispersions σ. These cluster between 0·7 and 3 km/sec. Since the receiver bandwidth corresponds to a dispersion of 0·6 km/sec, the distribution found may be resolution-limited (although a bandwidth correction has been applied). The hydrogen densities n_H range from 1 to 680 cm^{-3}, with 11 cm^{-3} as median; the masses from 2·6 to 2500 solar masses, with 115 as median. These values, however, depend on several assumptions. Correcting appropriately for incomplete resolution of components in the analysis, Clark derives a line density $k = 4$ kpc^{-1} for clouds of all optical depths together; within the Orion Arm, the value may be twice as high.

For the well-known difference in the appearance of 21-cm emission and absorption profiles—the latter show much stronger peaks—, Clark (1965) suggests the following explanation. The clouds observed in absorption may mostly have temperatures of the order of 100 °K. They may be surrounded by a tenuous medium, hotter than 1000 °K; this would have small optical depth and thus contribute little to the absorption profiles, but considerably to the emission.

*Cf. Section 6 for a discussion of this procedure.

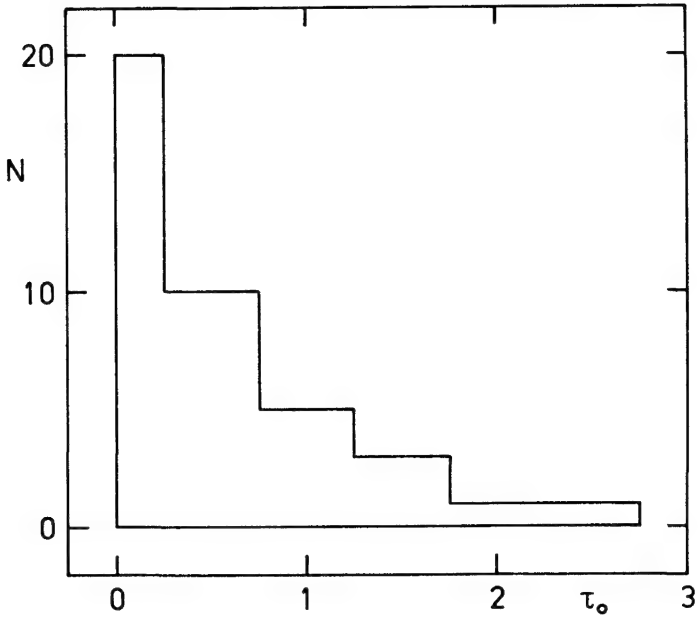

FIG. 2. Histogram of central optical depths, τ_0, of Gaussian components in the absorption spectra of strong discrete sources (Clark 1965). The ordinate in the interval $0{\cdot}0 < \tau_0 < 0{\cdot}25$ has been normalized to an interval of width 0·5.

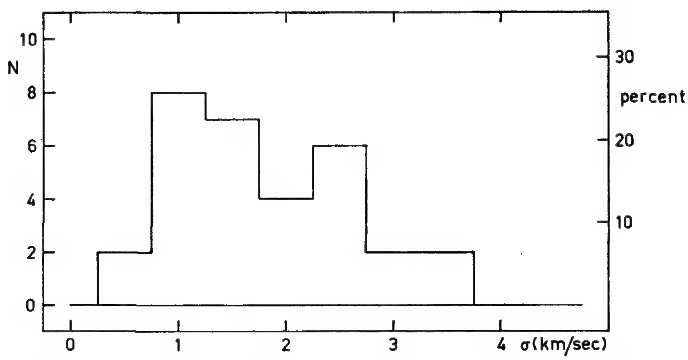

FIG. 3. Histogram of velocity dispersions, σ, of Gaussian components in the absorption spectra of strong discrete sources (adapted from Clark 1965, Tables 3 and 4).

Shuter and Verschuur (1964) have studied the spectra of three strong sources, with bandwidths as small as 0·6 km/sec. Their freehand analysis of the absorption profiles into Gaussian components appears less reliable than that by Clark; the numbers of components used are definitely higher than warranted.

An extensive survey of absorption spectra is underway at Green Bank (Menon and Williams, unpublished).

6. STUDIES OF 21-CM EMISSION

As mentioned in Section 2, the 21-cm line is observable in emission anywhere in the sky. However, for studies of the detailed structure and motions of hydrogen clouds one must avoid the galactic belt: at low latitudes the aerial beam samples such a large volume out of the layer of interstellar gas, that the contributions of individual 'clouds' (or whatever structural details one wishes to discern) are blended in the line profile and confused beyond recognition. At the galactic poles, the volume sampled is so small that one wonders whether it can be considered representative: a solid angle of one square degree contains only a fraction 10^{-8} of the whole gas disk! Also, at high latitudes no distance estimates from differential galactic rotation are possible. Thus, intermediate latitudes are probably the best choice for detailed investigations of the structure of the interstellar medium.

I shall in what follows distinguish two types of investigation:

(*a*) surveys covering large regions of sky with a (usually) wide grid;

(*b*) detailed studies of small regions, usually covered with a close grid of observations.

It will be clear that both have their merits and are indeed indispensable.

(*a*) *Surveys at intermediate and high latitudes*

Extensive surveys of the sky outside the galactic belt were made already several years ago. These surveys (Erickson and Helfer 1960, Helfer 1961; Davies 1960; McGee and Murray 1961, McGee *et al.* 1963, McGee and Milton 1964, McGee *et al.* 1966) have brought important information about the general distribution and motion of hydrogen in the solar neighbourhood, but limitations of angular and/or velocity resolution make them unsuitable for our present purpose. Some of the results are reviewed by Blaauw *et al.* (Paper 45), along with those of higher-resolution surveys carried out at Dwingeloo (Muller *et al.* 1966, Blaauw and Tolbert 1966, Hulsbosch and Raimond 1966, Tolbert and Fejes 1967).

At intermediate latitudes ($b^{\mathrm{I}} = +25°, +20°, +15°, +10°, -10°, -15°, -20°$), Groningen astronomers (Van Woerden *et al.* 1962) have observed a wide grid ($\Delta l = 10°$) of profiles with 2 km/sec receiver bandwidth and 0°.6 aerial beamwidth. In agreement with expectation, the profiles showed a considerable amount of structure, indicative of a possible resolution of the contributions from individual interstellar clouds. In an attempt to unravel this structure in a quantitative and reproducible fashion, Takakubo and Van Woerden (1966; see also Blaauw 1962) have analyzed the profiles into Gaussian components, following least-squares methods on an electronic computer. The process, which has the additional advantage of reducing a profile consisting of some 100 data points to a manageable set of parameters, has been described in extenso by Kaper *et al.* (1966). Similar procedures have been followed elsewhere. The examples given by Lindblad (Paper 24, Figure 7) are representative of the quality of fit obtained in the Groningen analyses.

Analysis of an optical-depth profile $\tau(V)$ of m points into n components:

$$\begin{cases} \tau_k(V) = \sum_{i=1}^{n} \tau_{0i} \exp\{-(V - V_{0i})^2/2\sigma_i^2\} + \Delta\tau_k, \\ S \equiv \sum_{k=1}^{m} (\Delta\tau_k)^2 \text{ to be minimized,} \end{cases} \tag{3}$$

yields 3 n component parameters: central optical depth τ_{0i}, average radial velocity V_{0i}, and velocity dispersion σ_i, which are properties of the group of atoms contributing component i to the profile; the surface density N_H (atoms cm^{-2}) of hydrogen in a group is proportional to $\tau_0\sigma$. Whether such groups of atoms are well-defined physical entities, and can be localized in space, remains to be seen; a good test is supplied by comparisons of component parameters found at neighbouring positions on the sky. The procedure of analysis has no unique solution; critical judgment is therefore necessary (Kaper *et al.* 1966, Section 5). The method has nevertheless found wide and successful application in studies of the structure and kinematics of the interstellar medium (Van Woerden 1962; Girnstein 1963, 1964, Girnstein and Rohlfs 1964; Dieter 1964, 1965; Clark 1965, cf. Section 5 above; Lindblad 1966, 1967; Schwarz and Van Woerden 1967, cf. Section 6*b* below). Schwarz (1967) has recently developed a simple method for an approximate component analysis, based on the second derivative of the profile; the method may serve to provide automatic (computer-determined) initial estimates for least-squares analysis.

Figure 4 summarizes the component parameters derived by Takakubo and Van Woerden (1966) from profiles in the $b^I = +15°$ zone of their Intermediate-Latitude Survey. The features at high velocities have been discussed by Blaauw (1962), by Blaauw and Tolbert (1966), and by Takakubo (1967*a*, Sections 2·4 and 2·5); see further Paper 45 in this volume. The low-velocity components in the Takakubo-Van Woerden (1966) catalogue have served as basis for an analysis by Takakubo (1967*a*) of the kinematics of neutral hydrogen in the solar neighbourhood. As is evident from Figure 4, the component velocities exhibit a marked effect of differential galactic rotation. The root-mean-square residual velocity, μ, is about 6 km/sec; Takakubo reaches no conclusion concerning the type of distribution of the residuals. He further finds that single (non-blended) components corresponding to individual interstellar clouds may be characterized by internal velocity dispersions, $\sigma \approx 2$ km/sec, and surface densities, $N_H \approx 2 \times 10^{20}$ atoms/cm^2. The instrumental profile has a dispersion of 0·85 km/sec. There are large numbers of components with dispersions σ between 3 and 7 km/sec, but these may not represent single clouds. Takakubo's comparisons of Ca^+ and H profiles are reviewed in Section 7.

The component parameters obtained from the Dwingeloo-Groningen Intermediate-Latitude Survey were further used in discussions of interstellar-cloud models by Takakubo (1963*a*) and Terauti (1963); see also Blaauw (1962). The surface densities N_H per component served as basis for these computations. Although at first sight it would seem that the assumptions made should strongly affect the derived model parameters, the results reported in Section 8 for different models are in rather good agreement.

(*b*) *Detailed studies of restricted regions*

In Takakubo's (1963*a*) model calculations, the (average) angular size of a cloud appeared to be a key unknown. From the wide-grid Intermediate-Latitude Survey, no direct determination of this angular size was possible. Additional observations were therefore taken, at positions closely spaced along lines of constant latitude or longitude (Van Woerden *et al.* 1962, Figure 1 and Section 4). Blaauw (1962, Figures 8 and 9) reported preliminary results of Gaussian analyses of some of these profiles. These results showed that some components continued over distances of 10° on the sky, while

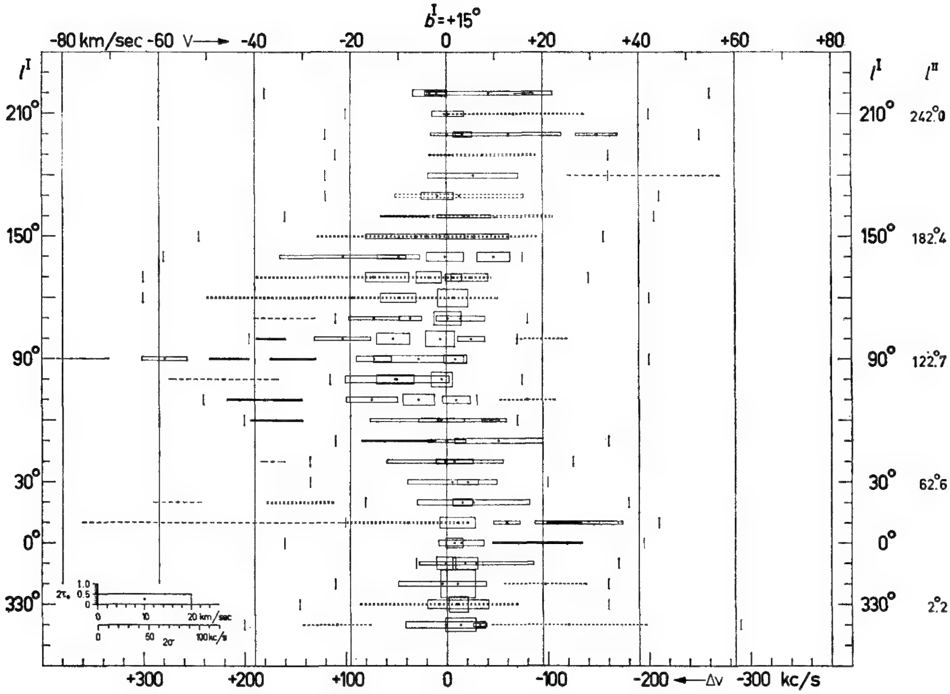

FIG. 4. Gaussian components of 21-cm profiles observed at $b^{\mathrm{I}} = +15°$ (Takakubo 1967*a*). The radial velocities, V, of the Gaussian components with respect to the local standard of rest are plotted versus the galactic longitude, l. Each component is represented by a rectangle with a dot at its centre. The position of the dot shows the longitude, l, of observation and the radial velocity, V, of the component; the height of the rectangle is proportional to the central optical depth, τ_0; its width indicates (twice) the velocity dispersion, σ; hence, the area of the rectangle is proportional to N_{H}, the number of hydrogen atoms per column of 1 cm² cross-section in the component. The scales of τ_0 and σ are shown in the lower left corner of the diagram.

Components significantly affected by stray radiation are shown dotted. Dashed lines represent components for which the parameters were obtained by eye estimate. Small vertical bars indicate the frequency (or, velocity) intervals in which the profiles were analyzed. Some profiles may contain components outside the interval shown here. Numerical values of the parameters are given in Table 1 of Takakubo and Van Woerden (1966).

others were no larger than one or two degrees; the latter result agreed better with the models calculated. A final report on this program is being prepared by Takakubo (1967*b*).

It is clear that better insight into the size and structure of clouds should be obtainable from two-dimensional grids of observations covering areas of the order of, say, ten by ten degrees. Many programs of this kind have been undertaken in the last few years. A complete listing of these detailed studies, including those covering smaller areas, would contain a few dozen items. Without critical discussion, it would be of limited value. Recent compilations have been made by Kerr (1967*a*, 1967*b*). I here restrict myself to a tabulation of studies fulfilling the following requirements (Table 1):

Table 1

A selection of detailed 21-cm studies of restricted regions

Reference	Observatory	Region	l^{II}	b^{II}	Beam (degrees)	Band (kHz)	σ_{instr} (km/sec)
Dieter (1964)	Harvard	NGP		+80 to +90	0·9	15	1·3
Dieter (1965)	Harvard	SGP		−80 to −90	0·9	15	1·3
Dieter (1965)	Harvard	NGP		+80 to +90	0·9	2	0·2
Heiles (1966*a*, 1966*b*, 1967)	Green Bank		100 to 140	+13 to +17	0·17	5	0·5
Van Woerden (1962, 1967); Schwarz and Van Woerden (1967)	Dwingeloo	Orion	202 to 212	−25 to −10	0·6	10	0·85
Schwarz (in preparation)	Dwingeloo	Cam	122 to 142	+20 to +30	0·6	8	0·7
Van Woerden and Schwarz (in preparation)	Dwingeloo	Sco	350 to 356	+14 to +20	0·6	10	0·85
Habing (in preparation)	Dwingeloo		75 to 95	−46 to −26	0·6	15	1·3
			310 to 340	+33 to +53	0·6	15	1·3

Notes: NGP = North Galactic Pole; SGP = South Galactic Pole; σ_{instr} = dispersion of instrumental profile

(*i*) galactic latitudes exceeding 10°;

(*ii*) beamwidth smaller than 1°;

(*iii*) bandwidth at most 15 kHz = 3 km/sec.

Mrs Dieter (1964, 1965) investigated both *galactic polar caps*, with bandwidths of 3 and 17 km/sec. In both areas, she found hydrogen falling down to the plane with considerable velocities (cf. Paper 45). Of more direct concern to us here are her narrow-band observations of the region around the galactic north pole. The Gaussian components of profiles in this region have dispersions ranging from 1·1 to 7 km/sec, with an average of 2·5 km/sec. Since the receiver passband was equivalent to a Gaussian of dispersion $\sigma_{\text{instr}} = 0{\cdot}2$ km/sec, this result is obviously not resolution-limited. Tracing related components on the sky, Mrs Dieter (1965) was able to determine cloud boundaries. Their diameters $2a$, densities n_{H}, and masses M depend on the distance. Assuming this to be 100 c pc, she finds the following average quantities: $2a = 9\ c$ pc, $n_{\text{H}} = 1{\cdot}8\ c^{-1}$ cm^{-3}, $M = 17\ c^2\ M_{\odot}$.

Heiles (1966*a*, 1967) has avoided the long job of Gaussian analysis. He presents his survey of 160 square degrees, about 5000 primary-beam areas, in the form of contour diagrams showing intensity as a function of right ascension and velocity for constant declinations. These diagrams, distributed in catalogue form (Heiles 1966*b*), are similar to the one illustrating Westerhout's Paper 28 in this volume. Heiles himself summarizes his analysis of these diagrams in Paper 5. Of particular interest are the '*cloudlets*', small concentrations of hydrogen, of which Heiles has found many hundreds in the diagrams. Their angular diameters, of the order of 0°5, are not so much larger than the beam of the Green Bank 300-foot (91-m) paraboloid; and the fact that their excess densities are not large may explain that these features have escaped attention in studies carried out with smaller telescopes. Figures 5 and 6 summarize the distributions of diameter, mass, density and internal velocity dispersion for the cloudlets. These quantities are again dependent on the distance, assumed by Heiles to be 500 pc for all these objects.

Following early work by Menon (1958), Van Woerden and Schwarz have made a detailed investigation of the *Orion region*. Line profiles of high accuracy, obtained with

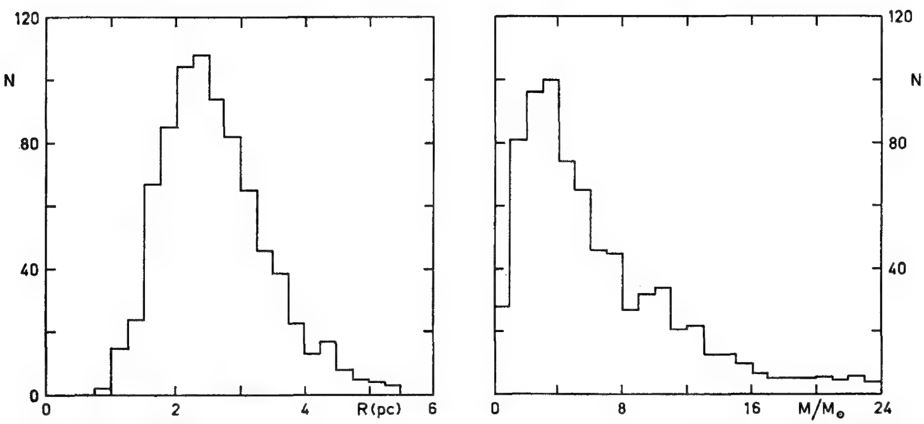

FIG. 5. Distributions of radii R and masses M_{H} of 'cloudlets' (Heiles 1966*a*, 1967).

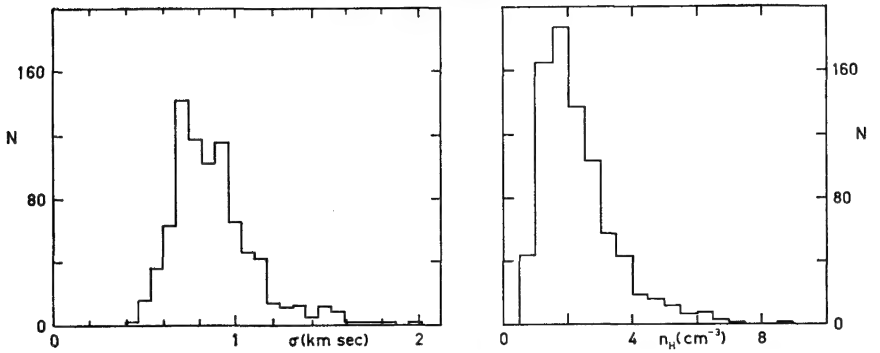

FIG. 6. Distributions of densities n_H and velocity dispersions σ of 'cloudlets' (Heiles 1966*a*, 1967).

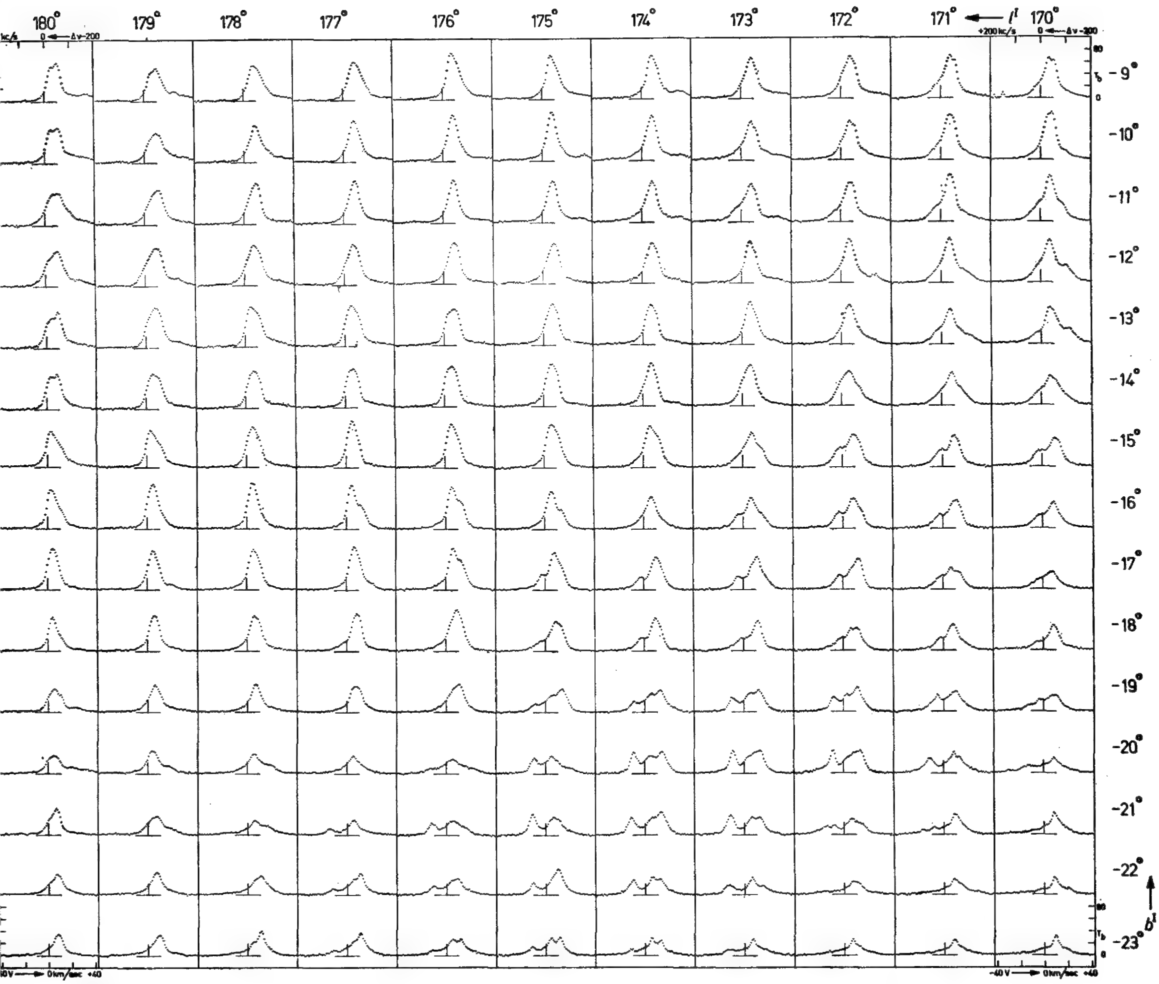

FIG. 7. Profiles $T_b(V)$ of the 21-cm line at 165 positions on a one-degree grid in the Orion region (Van Woerden 1962, 1967).

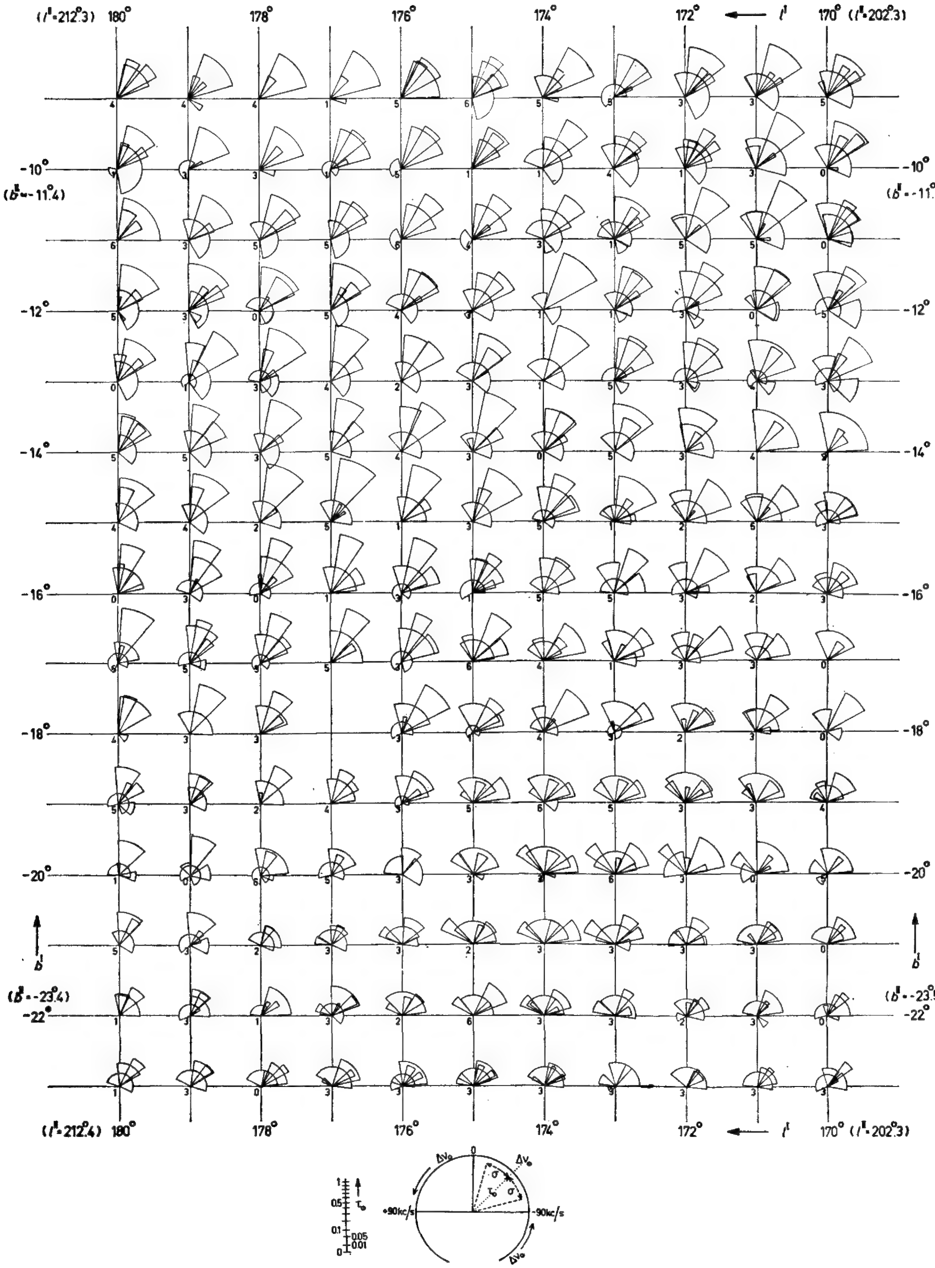

FIG. 8. Gaussian components of the profiles shown in Figure 7. Each profile is represented by a set of sectors, each corresponding to one profile component. The radius of the sector is a measure of the central optical depth τ_{0i} of the component (for scale, see bottom of the figure). The central line of the sector is tilted from the vertical at an angle proportional to the average frequency shift $\Delta\nu_{0i}$ of the component (or to its average radial velocity, V_{0i}; -90 kc/s $= +19$ km/sec). The aperture angle of the sector is proportional to the (velocity) dispersion σ_i of the component. The weight of the set of parameters displayed is shown just below the origin of the sectors (Schwarz and Van Woerden 1967).

2 km/sec bandwidth, are available at 400 positions. Figure 7 displays the profiles for 165 positions in a one-degree grid (Van Woerden 1962). There is a striking increase in complexity of the profiles, and in their variability with position, as one moves away from the galactic equator to latitudes of about $-20°$ (Van Woerden 1963). In their Gaussian-component analysis, Schwarz and Van Woerden (1967) have exercised great care to treat every profile independently, and to follow quantitative (non-subjective) criteria for choosing between the several solutions available for each profile.

Figure 8 summarizes the component parameters for the profiles displayed in Figure 7. The sector representation of components has the purpose to facilitate comparison of parameters, and of profile structure, across a two-dimensional sky map. From a diagram of this kind one can easily assess the amount of continuity in component structure, and outline the area occupied by a set of related components – that is (or may be), determine the boundaries of hydrogen clouds. The authors consider the velocity V_0 as the most important, and the central optical depth τ_0 as the least important, parameter in judging continuity; Schwarz is developing a quantitative method to remove the subjective element from this process. Figure 9 shows tentative outlines of clouds determined from the sector diagram. The angular sizes range from $1°$ to almost $10°$. Since the Orion Association is at 400 or 500 pc distance, the cloud diameters may lie between 8 and 80 pc if most of the observed hydrogen is at roughly the distance of the association. If there is much hydrogen in the foreground, the diameters would be smaller. Attempts to estimate the distance to the hydrogen remain to be made.

Figure 10 gives statistics of the velocity dispersions σ. Since component dispersions at neighbouring positions are in general correlated, I have determined the average dispersion for each cloud, neglecting the variations of σ with position. The wide bottom component visible in almost all profiles is absent from Figure 10; it is not clear whether it represents a separate physical entity or rather a conglomerate of weak, unresolved profile components. The distribution of average dispersions reaches from 1 to 6 km/sec, with a maximum between 2 and 3 km/sec.

Further information about the internal motions in a cloud comes from comparisons of the component velocities V_0 at neighbouring positions. Such comparisons are facilitated by diagrams like Figure 11, in which only the sectors representing one related set of components are drawn. The needles pointing in a fixed direction show the grand average of V_0 over a cloud, as a reference velocity. The diagram also indicates the surface-density variations in a cloud, since the sector areas are proportional to N_H.

For the studies of Camelopardalis and of the Scorpius-Ophiuchus region mentioned in Table 1, similar analyses have been carried out but are not so far advanced.

Many investigations have been concerned with *neutral hydrogen in associations and in galactic clusters*. I must refrain from a detailed review of these studies; for a recent brief summary see Raimond (1966). The general trend is that in most associations and young clusters, if not too unfavourably placed with respect to the galactic background, neutral hydrogen can indeed be detected. Around several associations, expanding shells of neutral hydrogen have been reported (Wade 1957, Menon 1958, Girnstein and Rohlfs 1964; see also Raimond 1966). However, the detailed relationships of structure and motions in the hydrogen to the processes of star birth in associations and to the subsequent evolution of H II regions around hot, young stars still deserve a great deal of attention.

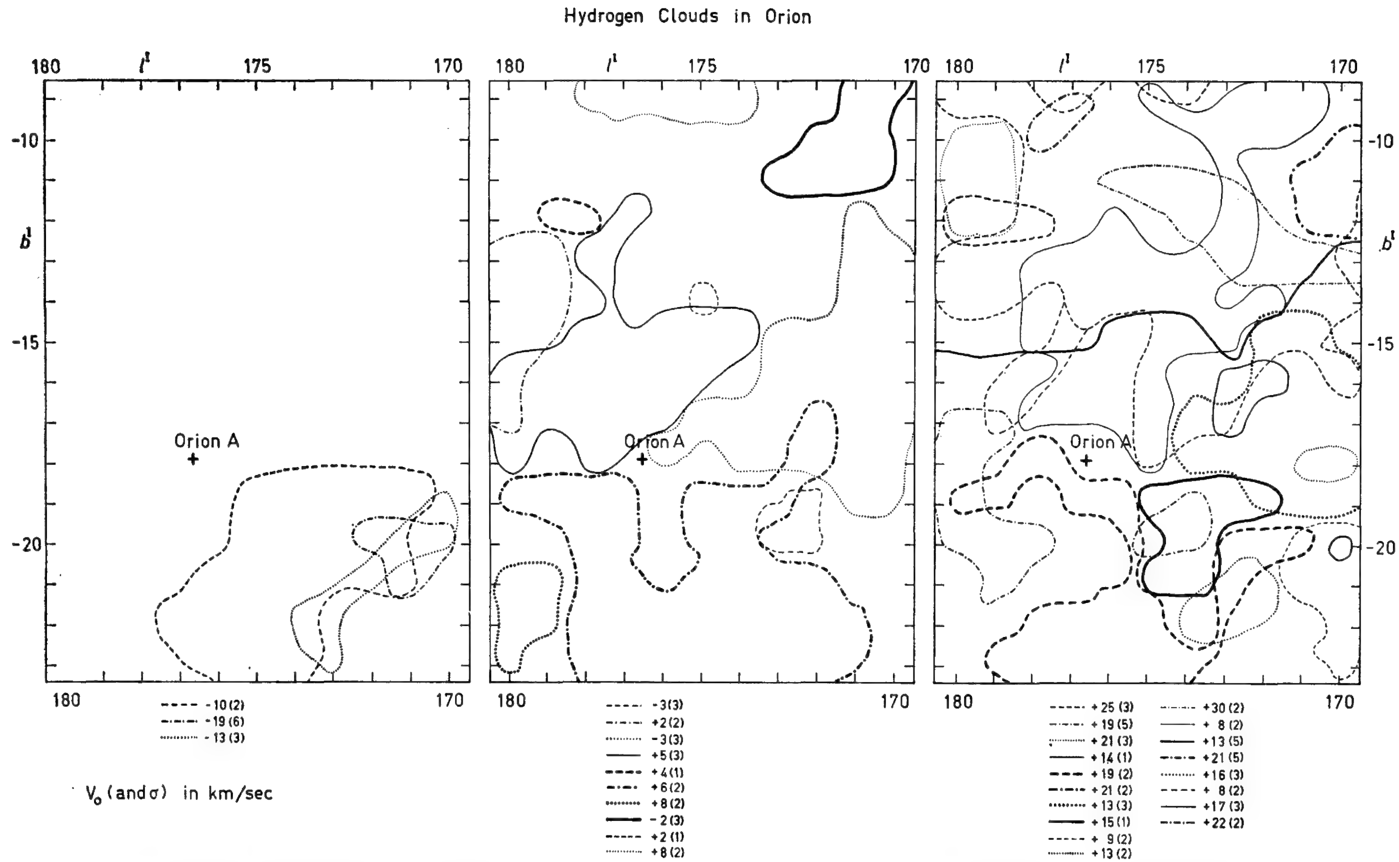

FIG. 9. Tentative delineation of hydrogen clouds in Orion. Each cloud's boundary is indicated by a different line. The key shows average velocity, V_0, and velocity dispersion, σ, for each cloud. The delineation of clouds is done in Figure 8 after consideration of the continuity of component parameters in neighbouring positions on the diagram. Cloud boundaries are influenced by the unavailability of component analysis for $l^1 = 177°$, $b^1 = -18°$ (near Orion A). (Schwarz and Van Woerden 1967).

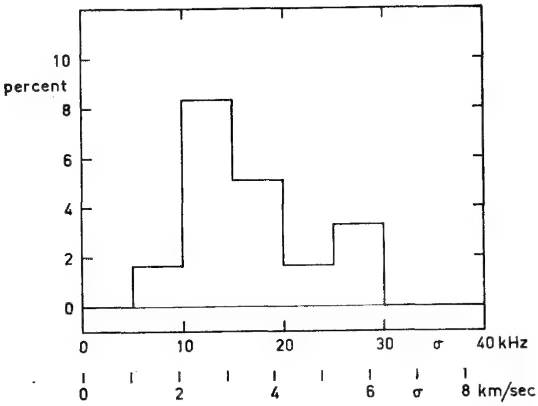

FIG. 10. Histogram of velocity dispersions, σ, of Gaussian components in the 21-cm profiles in the Orion region. The dispersions considered are averages over the face of a cloud as defined in Figure 9 (Schwarz and Van Woerden 1967).

7. COMPARISON OF OPTICAL AND RADIO INTERSTELLAR LINES

The most extensive and detailed data on interstellar structure and motions come from the optical absorption lines of Ca^+ at 3934 and 3968 Å and from the radio emission line of H at 21 cm wavelength. Direct comparison of the two sets of data is thus of interest. Ideally, one should compare observations taken with similar angular and velocity resolutions, and at the same positions.

As noted in Section 4, velocity resolutions of 3 km/sec, even of better than 1 km/sec, have recently come within reach also for the optical interstellar lines; but very few results are available so far, and the velocity resolution of published 21-cm observations is generally far superior. Far worse is the situation regarding angular resolution: a B0-star at 400 pc distance subtends a solid angle of less than 10^{-14} square degrees! Table 2 summarizes three sizable sets of comparisons. In all three, the Ca^+ data used are those by Adams (1949). The 21-cm observations vary widely as regards velocity resolution and position deviation. In comparing the velocities of Ca^+ and H components, Takakubo

Table 2

Velocity comparisons of calcium K-line and hydrogen 21-cm line components

Reference	Source of 21-cm data	Beam (degrees)	Band (km/sec)	Δp (degrees)	$\mu(\Delta V)$ (km/sec)
Howard *et al.* (1963)	McGee *et al.* (1961)	2·2	7	0·35	3 ± 1
Takakubo (1967*a*)	Van Woerden *et al.* (1962)	0·56	2·0	2·5	1·3
Van Woerden and Baas	Dwingeloo	0·63	1·7	0·0	1

Notes: Δp = average position difference
$\mu(\Delta V)$ = root-mean-square velocity difference, Ca − H, after correction for measuring errors

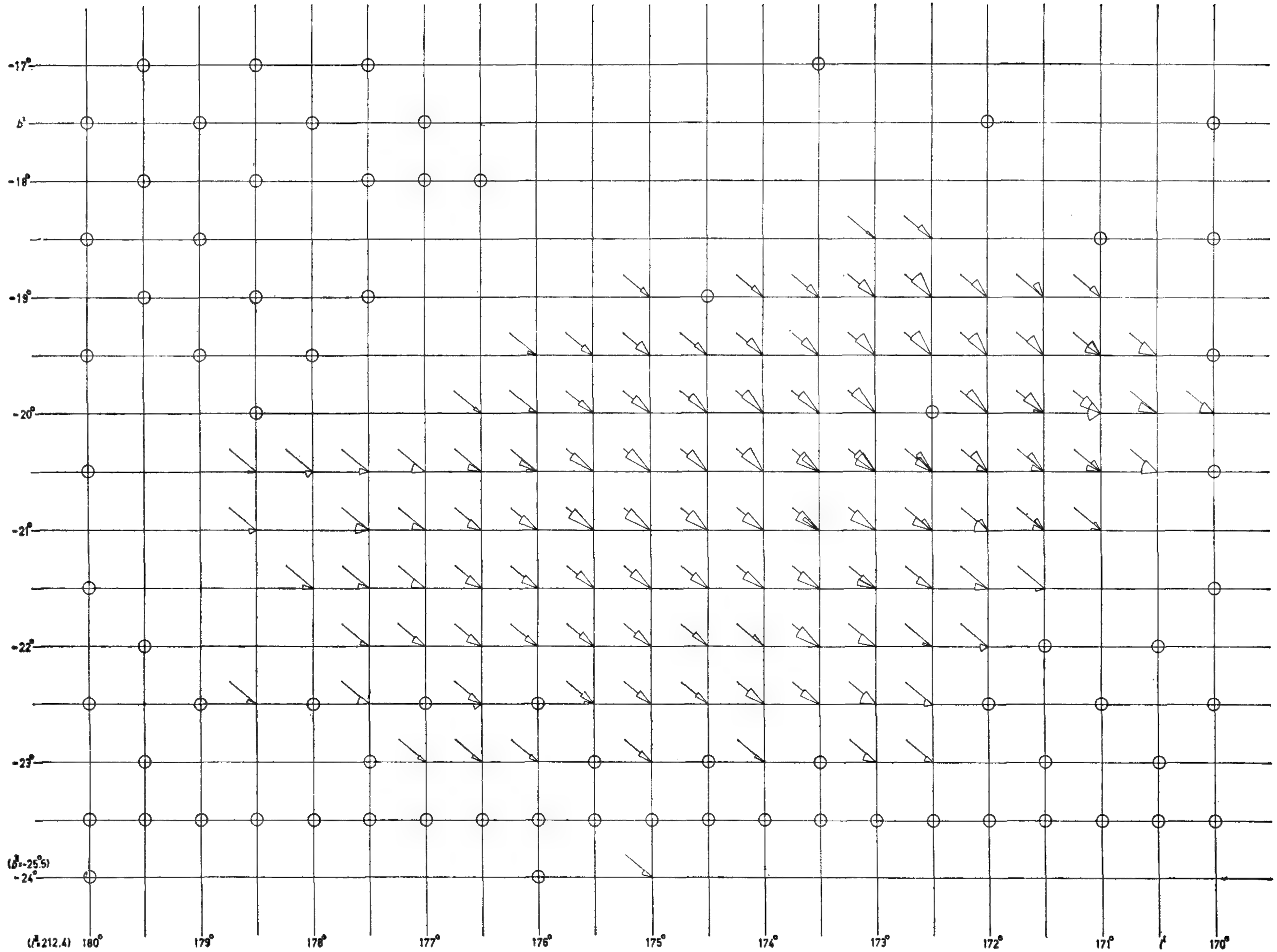

FIG. 11. Differential motions and variations of surface density in a hydrogen cloud. The sectors for the clouds shown in the left-hand panel of Figure 9 are here brought together. Their meaning is the same as in Figure 8. The needles pointing in a fixed direction indicate the average velocity for these hydrogen clouds and serve as a velocity reference. Circles indicate unobserved positions. Blank spaces mean: component absent (Schwarz and Van Woerden 1967).

(1967*a*) as well as Van Woerden and Baas rejected cases where no correlation was in evidence, while Howard *et al.* (1963) included cases of single Ca^+ components deviating strongly in velocity from the strongest 21-cm peak. Thus, the dispersion of velocity differences found by Howard *et al.* is naturally somewhat larger. Nevertheless, the velocity agreement is on the average remarkably close, indicating that both components are generally formed in volumes having little (average) relative motion.

A more detailed discussion should consider the detailed shapes of the line profiles. The observations by Adams (1949) are not well suited to this purpose, since their velocity resolution is insufficient. Takakubo (1963*b*) has compared the K-line profile in ϵ Ori, measured at a resolution of about 3 km/sec, with the 21-cm line profile at a nearby position, taken with 2 km/sec bandwidth. Most of the profile components agreed well in velocity, but the intensity ratios differed considerably. A similar conclusion was reached by Takakubo (1967*a*) in his comparisons mentioned above (Table 2).

My own high-resolution K-line profiles obtained recently at the Mount Wilson 100-inch coudé (cf. Section 4) offer excellent possibilities for comparison. Figure 12 shows microphotometer tracings of the Ca^+ K line in three stars in or near the Orion Nebula, together with a 21-cm profile measured nearby and analyzed into Gaussian components. The strong 21-cm component at $V = +11$ km/sec agrees closely with a K component in both 42 and ι Ori (and in other stars in the region); θ^1 Ori C, the brightest O star in the core of the Orion Nebula is discordant. The broader 21-cm component at $+6$ km/sec may also be present in both 42 and ι Ori. For the other components of both K line and 21-cm line, there is little or no agreement. From further comparisons not shown here, it appears that correspondence is generally close for K-line components recognizable over considerable areas on the sky. Components which do not repeat in nearby stars tend to be lacking in the 21-cm profile as well. A cloud of small angular size seen in absorption against a star may be lost in the wide beam of a 21-cm observation; ionization of the cloud's hydrogen is another possible explanation.

We conclude from this section that calcium and hydrogen profiles tend to agree in general respects, but to differ in detail.

8. STRUCTURE OF THE INTERSTELLAR MEDIUM

We shall now summarize the information on structural details in the interstellar medium discussed in the previous sections. Table 3 compiles the data from various recent sources, together with quantities taken from earlier analyses. The bulk of the new information is from studies of the 21-cm line, mostly in emission, partly also in absorption; even in the analysis of visual extinction, Scheffler (1967*b*) has used data from 21-cm absorption.

Most of the new values in Table 3 are in remarkable agreement. However, the data are far from complete and they are biased. The low galactic latitudes have been avoided, and the hydrogen in the great associations is hardly represented. (Just to keep the balance, and because no distance estimates are available yet for the clouds in Orion delineated by Schwarz and Van Woerden, I have added a few numbers from Raimond (1966) for hydrogen clouds in the association II Mon.) The values quoted for Heiles, and to some extent also those given for Takakubo and Terauti, refer to the smallest details discernible in the observations. The fact that recent values for cloud size and mass are smaller than those given in the earlier reviews is due partly to such selection

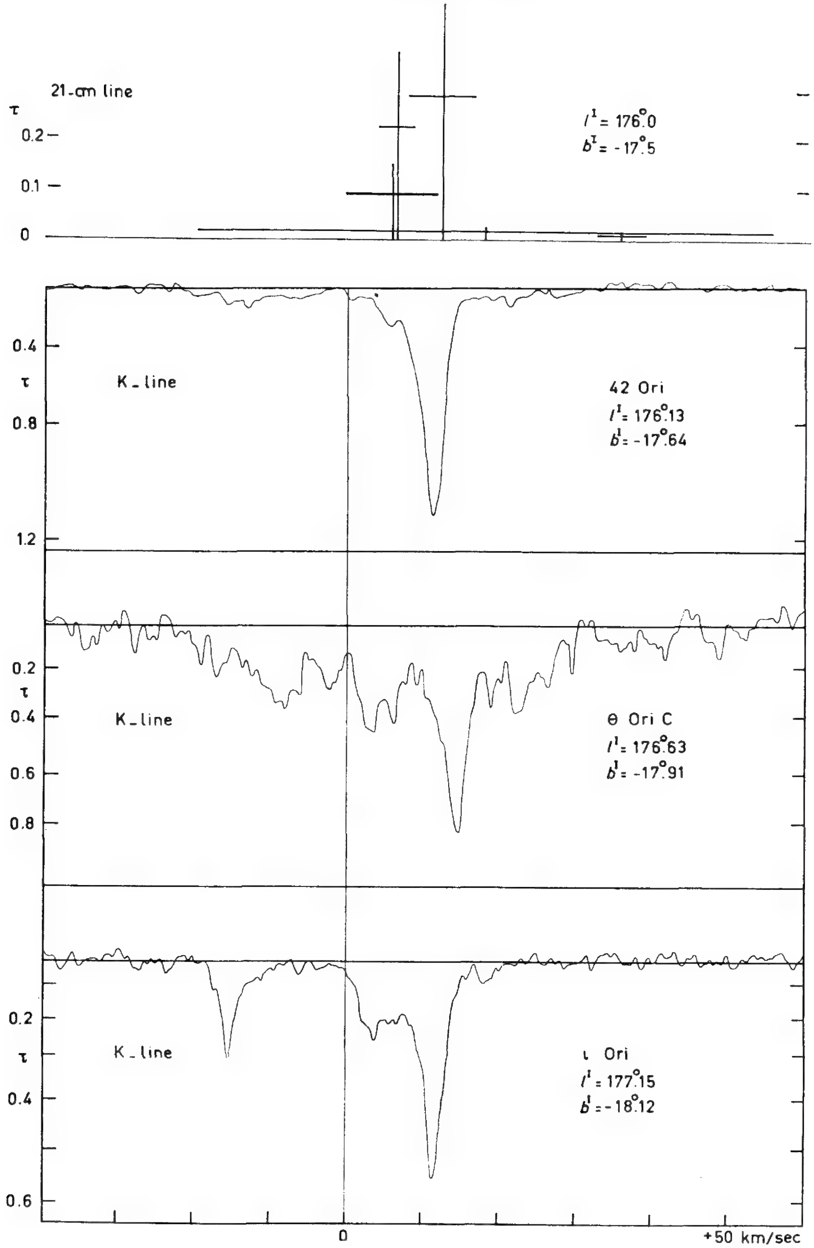

FIG. 12. Comparison of three K-line profiles and a 21-cm profile. The stellar spectra have been observed at Mount Wilson, at 1·1 Å/mm, and the K lines microphotometered. The star θ^1 Ori C is in the core of the Orion Nebula; 42 and ι Ori are about one Dwingeloo beamwidth away. The five crosses in the top section of the figure indicate Gaussian component parameters of the 21-cm profile at $l^{I} = 176°.0$, $b^{I} = -17°.5$.

Table 3

Interstellar cloud parameters

Reference		Notes	$2R$ (pc)	$\mathfrak{N}_0$ (kpc^{-3})	k (kpc^{-1})	f	M_H ($M_\odot$)	n_H (cm^{-3})	$10^{-20} N_H$ (cm^{-2})
Strömgren Van de Hulst	(1948) (1958)	1	20	20 000	7	0·10	600	6	8
Strömgren	(1948)	2	15				2 500	60	28
Oort	(1954)	3	60				30 000	10	18
Spitzer	(1967)	4	14	50 000	8	0·07	400	10	4
Spitzer	(1967)	5	30	1 000	0·7	0·007	7 000	20	18
Spitzer	(1967)	6	8				800	100	25
Takakubo	(1963*a*)	7	7	300 000	11	0·05	54	14	3
Terauti	(1963)	8	16	70 000	14	0·14	264	4·6	2·3
Dieter	(1965)	9	9				17	1·8	0·5
Clark	(1965)	10	10		8		59	8	2·6
Raimond	(1966)	11	40				6 000	8	10
Heiles	(1966*a*, 1967)	12	5				4	2	0·3
Scheffler	(1967*b*)	13	3		5		25	70	6
Scheffler	(1967*b*)	14	25		0·5		15 000	70	55

Column headings: $2R$ = diameter; $\mathfrak{N}_0$ = number density of clouds in space, near galactic plane; k = line density of clouds, near galactic plane; f = fraction of space occupied by clouds ('filling factor'); M_H = mass of neutral hydrogen in cloud; n_H = number density of hydrogen atoms in cloud; N_H = surface density of hydrogen on line of sight through cloud centre.

Notes:

1. 'Average' interstellar cloud, data from extinction and from optical interstellar absorption lines.
2. Dense cloud in front of χ^2 Ori.
3. Large cloud complexes (e.g. in Taurus).
4. 'Standard' cloud, cf. note 1.
5. 'Large' cloud, from statistics of colour excesses (Schatzman 1950, Münch 1952).
6. Intermediate-sized dark cloud, adapted from Bok.
7. Single interstellar cloud, from statistics of N_H per profile component in Intermediate-Latitude Survey. Model: equal, homogeneous, spherical clouds.
8. Spherical cloud + shell of double size and half density, cf. note 7.
9. Four clouds in region of North Galactic Pole, from continuity in profile component parameters. Assumed distance 100 pc.
10. Twenty-three components of absorption spectra of strong radio sources (Clark's Table 4); Ori A excluded.
11. Three clouds in association II Mon.
12. Averages for 815 'cloudlets' in survey of Table 1. Assumed distance 500 pc.
13. From statistics of visual extinction, 'small clouds'.
14. From statistics of visual extinction, 'compact big clouds'.

effects, and partly to the increased sensitivity of 21-cm receivers, which has made possible effective, detailed studies of hydrogen at high and intermediate galactic latitudes. There is no doubt that condensations in spiral arms of 100 pc diameter still exist; McGee (1964), who lists three local hydrogen complexes averaging 140 pc in size and 4 cm^{-3} in density, even calls attention to complexes in spiral arms with sizes ranging from 500 to 2500 pc and densities of the order of 0·5 cm^{-3}. On the other hand, the globules of 0·1 to 0·5 pc size and the even narrower filaments are still beyond the reach of radio astronomers. Thus, rather than quoting parameters for standard interstellar clouds, we should keep in mind the great variety in sizes, masses and forms—as indeed has been done before by Van de Hulst (1958), Spitzer (1967), and others.

9. MOTIONS IN THE INTERSTELLAR MEDIUM

In this section we shall discuss two types of motion only: motions of interstellar 'clouds' (whatever this term may mean) with respect to their surroundings (say, a group of clouds), and motions of atoms and cloud elements within a cloud. The motions of groups of clouds, representing deviations from circular galactic rotation, fall outside the scope of this review; they are considered by Lindblad in Paper 24. For the motions of clouds in a group, and those of atoms in a cloud, we investigate only the solar neighbourhood, out to not more than 1000 pc, say.

(*a*) *External motions*

As to the motions of interstellar clouds with respect to their surroundings ('external' motions), two types of distribution have usually been considered: the exponential distribution (1) (cf. Section 4), and the Gaussian (2)—with V and V_0 replaced by V_0 and $\bar{V}_0$. Since my review of the subject at the Hamburg IAU Assembly (Van Woerden 1966), little new information has become available. The attempt by Takakubo (1967*a*), in his kinematical analysis of the Intermediate-Latitude Survey (cf. Section 6*a*), to determine the type of distribution for the residual velocities of the 21-cm components was unsuccessful, owing to anisotropy in the observed motions. Table 4 summarizes

Table 4

External motions of interstellar clouds

(only motions in line of sight considered)

Reference		Type of data	η (km/sec)	σ (km/sec)
Blaauw	(1952)	K-line velocities (Adams 1949)	5	
Münch	(1957)	Doublet ratios in Orion Arm: D_1 and D_2	3·3(Na)	
		Doublet ratios in Orion Arm: H and K	5 (Ca)	
Westerhout	(1957)	21-cm profile wings	6	6
Takakubo	(1958)	K-line velocities (Adams 1949)	7	
Takakubo	(1967*a*)	21-cm component velocities at intermediate latitudes	(4·5)	6
Average			5	(7)

Note: for an exponential distribution, $\sigma = \eta\sqrt{2}$

Table 5

Internal motions in interstellar clouds
(only motions in line of sight considered)

Reference		Atom	Region	Dispersions (km/sec) (corrected for broadening) Range	Average	Notes	σ_{instr} (km/sec)
Spitzer and Skumanich	(1952)	Ca^+		2 to 5	3·4		4
Muller	(1959)	H	abs.	1·0 to 2·6	1·8		0·4
Takakubo	(1963*b*)	Ca^+	ϵ Ori	1·0 to 3·3			1·2
Van Woerden	(1964, 1966)	Ca^+		1 and up			1
Dieter	(1965)	H	NGP	1·1 to 7	2·5		0·2
Clark	(1965)	H	abs.	0·6 to 3	1·8		0·6
Heiles	(1966*a*, 1967)	H		0·6 to 1·2	0·9		0·5
Takakubo and Van Woerden	(1966)	H	IB	0·85 and up			0·4
Takakubo	(1963*a*, 1967*a*)	H	IB	1 to 7	(2)	1	0·85
Schwarz and Van Woerden	(1967)	H	Orion	1·7 to 5·6	3·3	2	0·85

Notes:

1. The Heiles dispersions relate exclusively to 'cloudlets', cf. Section 6*b*.
2. The dispersions considered are averages of the component dispersions over all positions occupied by one particular cloud, cf. Figure 10.

Other entries refer to individual profile components.
NGP = north galactic pole; IB = intermediate latitudes; abs. = absorption spectra.

the best current data on external cloud motions in the solar neighbourhood. We note that high-velocity objects have generally been ignored in these determinations. The present status is that the low velocities can be represented somewhat better by exponential distributions (with $\eta \approx 5$ km/sec) than by Gaussians. In other regions, the situation may be different. For instance, Münch (1965) finds considerably higher values of η in the Perseus Arm.

(*b*) *Internal motions and temperature*

For the internal motions in interstellar clouds, Gaussian distributions have been almost exclusively considered. The detailed component analysis of 21-cm profiles (cf. Sections 6*a* and 6*b*) has furnished a wealth of material concerning this issue; most of it is compiled in Table 5. The dispersions σ listed are corrected for instrumental broadening where necessary, and most of the results do not appear seriously affected by this correction.

The variations in σ are so large that they must be considered real; it would seem difficult to ascribe them to blending of components with almost equal velocities. If the internal motions in the clouds were only thermal, the kinetic temperature T_k of the gas would follow directly from

$$T_k = m_H \sigma^2 / k = 121\ \sigma^2 \quad , \tag{4}$$

with T_k in degrees Kelvin, and σ in km/sec. The dispersions listed in Table 5 would then correspond to gas temperatures ranging from 44 to 6000 °K. Non-thermal mass motions are, however, likely to be responsible for at least part of the observed dispersions. A separation of the thermal and 'turbulent' motions has been achieved by Barrett *et al.* (1964) via a comparison of components in OH and hydrogen profiles; the irregular behaviour of OH (cf. Paper 7), however, makes one cautious about this procedure.

Direct information on the gas temperature is distressingly sparse, largely as a result of the discrepancies between the absorption profiles of radio sources and the emission profiles measured in the surroundings (cf. Section 5). These very discrepancies, as well as selfabsorption effects observed in the 21-cm line emission, do point to the presence of considerable variations in the gas temperature. Also, the theory of heating and cooling in the interstellar gas makes such variations appear highly probable; for a recent review see Kahn and Dyson (1965). On the observational side, it would seem that extensive measures at high angular and velocity resolutions are required to sort out the thermal and the non-thermal mass motions. A study of many discrete sources with a large paraboloid would be very useful. Also, interferometry—including the application of synthesis techniques—opens great possibilities.

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REFERENCES

Adams, W. S. 1941, *Astrophys. J.*, **93**, 11.
Adams, W. S. 1943, *Astrophys. J.*, **97**, 105.
Adams, W. S. 1949, *Astrophys. J.*, **109**, 354.
Akabane, K., Kerr, F. J. 1965, *Austr. J. Phys.*, **18**, 91.
Barrett, A. H., Meeks, M. L., Weinreb, S. 1964, *Nature*, **202**, 475.
Beals, C. S. 1936, *Mon. Not. R. astr. Soc.*, **96**, 661.
Blaauw, A. 1952, *Bull. astr. Inst. Netherl.*, **11**, 459.
Blaauw, A. 1962, in *The Distribution and Motion of Interstellar Matter in Galaxies*, Ed. L. Woltjer, W. A. Benjamin, Inc., New York, p. 48.
Blaauw, A., Tolbert, C. R. 1966, *Bull. astr. Inst. Netherl.*, **18**, 405.
Bystrova, N. V., Gosačinskij, I. V., Egorova, T. M., Ryžkova, N. F. 1964*a*, *Izv. glav. astr. Obs. Pulkove*, **23**, no. 5, 111.
Bystrova, N. V., Gosačinskij, I. V., Egorova, T. M., Ryžkova, N. F. 1964*b*, *Izv. glav. astr. Obs. Pulkove*, **23**, no. 5, 116.
Bystrova, N. V., Gosačinskij, I. V., Egorova, T. M., Ryžkova, N. F. 1965, *Izv. glav. astr. Obs. Pulkove*, **24**, no. 2, 202.
Clark, B. G. 1965, *Astrophys. J.*, **142**, 1398.
Clark, B. G., Radhakrishnan, V., Wilson, R. W. 1962, *Astrophys. J.*, **135**, 151.
Davies, R. D. 1960, *Mon. Not. R. astr. Soc.*, **120**, 483.
Dieter, N. H. 1964, *Astr. J.*, **69**, 288.
Dieter, N. H. 1965, *Astr. J.*, **70**, 552.
Dieter, N. H., Goss, W. M. 1966, *Rev. mod. Phys.*, **38**, 256.

Dorschner, J. 1967, *Astr. Nachr.*, **289**, 217.
Dorschner, J., Gürtler, J. 1963, *Astr. Nachr.*, **287**, 257.
Dorschner, J., Gürtler, J. 1966, *Astr. Nachr.*, **289**, 57.
Egorova, T. M. 1963, *Astr. Zu.*, **40**, 382 (translation in *Soviet Astr.*, **7**, 290).
Egorova, T. M. 1964, *Izv. glav. astr. Obs. Pulkove*, **24**, no. 1, 77.
Erickson, W. C., Helfer, H. L. 1960, *Astr. J.*, **65**, 1.
Girnstein, H. G. 1963, *Sber. Heidelberger Akad. Wiss., Math.-nat. wiss. Kl.*, Jahrgang 1962/63, 2.Abh., 101.
Girnstein, H. G. 1964, *Forschungsberichte des Landes Nordrhein-Westfalen*, no. 1366.
Girnstein, H. G., Rohlfs, K. 1964, *Z. Astrophys.*, **59**, 83.
Heiles, C. 1966*a*, *Observations of the Spatial Structure of Interstellar Hydrogen*, Ph. D. thesis, Princeton Univ.
Heiles, C. 1966*b*, *Catalog of Hydrogen-Line Data at Intermediate Latitudes*, Nat. Radio-Astr. Obs., Green Bank, West Virginia.
Heiles, C. 1967, *Astrophys. J.*, in press.
Helfer, H. L. 1961, *Astr. J.*, **66**, 160.
Herbig, G. H. 1963, *J. quantit. Spectrosc. radiat. Transfer*, **3**, 529.
Hobbs, L. M. 1965, *Astrophys. J.*, **142**, 160.
Hobbs, L. M. 1966, in Lick Observatory Report, *Astr. J.*, **71**, 782.
Howard, W. E., Wentzel, D. G., McGee, R. X. 1963, *Astrophys. J.*, **138**, 988.
Hulsbosch, A. N. M., Raimond, E. 1966, *Bull. astr. Inst. Netherl.*, **18**, 413.
Kahn, F. D., Dyson, J. E. 1965, *A. Rev. Astr. Astrophys.*, **3**, 47.
Kaper, H. G., Smits, D. W., Schwarz, U. J., Takakubo, K., Van Woerden, H. 1966, *Bull. astr. Inst. Netherl.*, **18**, 465.
Kerr, F. J. 1967*a*, in *Interstellar Matter*, Ed. L. H. Aller, Vol. VII in the series: *Stars and Stellar Systems*, Univ. Chicago Press, Chicago, chapter 12.
Kerr, F. J. 1967*b*, Radio Line Emission and Absorption in the Galaxy, in *Draft Rep. int. astr. Un.*, Comm. 40.
Lindblad, P. O. 1966, *Bull. astr. Inst. Netherl. Suppl. Ser.*, **1**, 177.
Lindblad, P. O. 1967, *Bull. astr. Inst. Netherl.*, **19**, 34.
Livingston, W. C., Lynds, C. R. 1964, *Astrophys. J.*, **140**, 818.
Lynds, B. T. 1962, *Astrophys. J. Suppl. Ser.*, **7**, 1.
McGee, R. X. 1964, IAU Symposium, no. 20, *The Galaxy and the Magellanic Clouds*, Eds. F. J. Kerr and A. W. Rodgers, p. 126, Austr. Acad. Sci., Canberra.
McGee, R. X., Milton, J. A. 1964, *Austr. J. Phys.*, **17**, 128.
McGee, R. X., Murray, J. D. 1961, *Austr. J. Phys.*, **14**, 260.
McGee, R. X., Murray, J. D., Milton, J. A. 1963, *Austr. J. Phys.*, **16**, 136.
McGee, R. X., Milton, J. A., Wolfe, W. 1966, *Austr. J. Phys. Astrophys. Suppl.*, no. 1.
Menon, T. K. 1958, *Astrophys. J.*, **127**, 28.
Morton, D. C. 1966, *Astr. J.*, **71**, 172.
Morton, D. C. 1967, *Astrophys. J.*, **147**, 1017.
Morton, D. C., Spitzer, L. 1966, *Astrophys. J.*, **144**, 1.
Muller, C. A. 1959, IAU Symposium, no. 9, *Paris Symposium on Radio Astronomy*, Ed. R. N. Bracewell, p. 360, Stanford University Press, Stanford.
Muller, C. A., Raimond, E., Schwarz, U. J., Tolbert, C. R. 1966, *Bull. astr. Inst. Netherl. Suppl. Ser.*, **1**, 213.
Münch, G. 1952, *Astrophys. J.*, **116**, 575.
Münch, G. 1957, *Astrophys. J.*, **125**, 42.
Münch, G. 1965, in *Galactic Structure*, Eds. A. Blaauw and M. Schmidt, Vol. V in the series: *Stars and Stellar Systems*, Univ. of Chicago Press, Chicago, p. 203.
Münch, G. 1967, in *Interstellar Matter*, Ed. L. H. Aller, Vol. VII in the series: *Stars and Stellar Systems*, Univ. of Chicago Press, Chicago, in press.

Münch, G., Unsöld, A. 1962, *Astrophys. J.*, **135**, 711.

Münch, G., Vaughan, A. H. 1966, in A. Rep. Director Mount Wilson and Palomar Obs., *Carnegie Instn Washington Year Book*, **65**, p. 153.

Münch, G., Zirin, H. 1961, *Astrophys. J.*, **133**, 11.

Neckel, Th. 1966, *Z. Astrophys.*, **63**, 221.

Oke, J. B. 1959, in A. Rep. Director Mount Wilson and Palomar Obs., *Carnegie Instn Washington Year Book*, **58**, p. 55.

Oort, J. H. 1954, *Bull. astr. Inst. Netherl.*, **12**, 177.

Raimond, E. 1966, *Bull. astr. Inst. Netherl.*, **18**, 191.

Ryžkova, N. F., Egorova, T. M., Gosačinskij, I. V., Bystrova, N. V. 1963, *Astr. Zu.*, **40**, 17 (translation in *Soviet Astr.*, **7**, 12).

Ryžkova, N. F., Egorova, T. M., Gosačinskij, I. V., Bystrova, N. V. 1964, *Izv. glav. astr. Obs. Pulkove*, **23**, no. 3, 3.

Schatzman, E. 1950, *Ann. Astrophys.*, **13**, 367.

Scheffler, H. 1966, *Z. Astrophys.*, **63**, 267.

Scheffler, H. 1967*a*, *Z. Astrophys.*, **65**, 60.

Scheffler, H. 1967*b*, *Z. Astrophys.*, **66**, 33.

Schlüter, A., Schmidt, H., Stumpff, P. 1953, *Z. Astrophys.*, **33**, 194.

Schwarz, U. J. 1967, *Bull. astr. Inst. Netherl.*, **19**, in preparation.

Schwarz, U. J., Van Woerden, H. 1967, *Bull. astr. Inst. Netherl.*, in preparation; preprint distributed at Noordwijk Symposium.

Shuter, W. L. H., Verschuur, G. L. 1964, *Mon. Not. R. astr. Soc.*, **127**, 387.

Spitzer, L. 1967, in *Interstellar Matter*, Ed. L. H. Aller, Vol. VII in the series: *Stars and Stellar Systems*, Univ. of Chicago Press, Chicago, chapter 9.

Spitzer, L., Skumanich, A. 1952, *Astrophys. J.*, **116**, 452.

Strömgren, B. 1948, *Astrophys. J.*, **108**, 242.

Takakubo, K. 1958, *Publ. astr. Soc. Japan*, **10**, 176 and 187.

Takakubo, K. 1963*a*, *Sci. Rep. Tôhoku Univ.*, Ser. I, **47**, 65 (also in *Sendai astr. Rap.*, no. 85).

Takakubo, K. 1963*b*, *Sci. Rep. Tôhoku Univ.*, Ser. I, **47**, 108 (also in *Sendai astr. Rap.*, no. 86).

Takakubo, K. 1967*a*, *Bull. astr. Inst. Netherl.*, **19**, 125.

Takakubo, K. 1967*b*, *Bull. astr. Inst. Netherl.*, in preparation.

Takakubo, K., Van Woerden, H. 1966, *Bull. astr. Inst. Netherl.*, **18**, 488.

Terauti, R. 1963, *Sci. Rep. Tôhoku Univ.*, Ser. I, **47**, 114 (also in *Sendai astr. Rap.*, no. 87).

Tolbert, C. R., Fejes, I. 1967, *Bull. astr. Inst. Netherl. Suppl. Ser.*, in preparation; preprint distributed at Noordwijk Symposium.

Van de Hulst, H. C. 1958, *Rev. mod. Phys.*, **30**, 913 (also in 1958, IAU Symposium, no. 8, *Cosmical Gas Dynamics*, Eds. J. M. Burgers and R. N. Thomas).

Van den Bergh, S. 1966, *Astr. J.*, **71**, 990.

Van Woerden, H. 1962, *De Neutrale Waterstof in Orion*, Doctor's Thesis, Groningen Univ.

Van Woerden, H. 1963, *Astr. J.*, **68**, 296.

Van Woerden, H. 1964, in A. Rep. Director Mount Wilson and Palomar Obs., *Carnegie Instn Washington Year Book*, **63**, p. 23.

Van Woerden, H. 1966, *Trans. int. astr. Un.*, **12B**, 391.

Van Woerden, H. 1967, *Bull. astr. Inst. Netherl.*, in preparation.

Van Woerden, H., Takakubo, K., Braes, L. L. E. 1962, *Bull. astr. Inst. Netherl.*, **16**, 321.

Vaughan, A. H., Münch, G. 1966, *Astr. J.*, **71**, 184.

Wade, C. M. A. 1957, Ph. D. Thesis Harvard Univ., and *Astr. J.*, **62**, 148.

Westerhout, G. 1957, *Bull. astr. Inst. Netherl.*, **13**, 201.

Whipple, F. L. 1948, in Centennial Symposia, *Harvard Obs. Monograph*, no. 8, p. 109.

Discussion

Miss A. B. Underhill: Some of the stars in Orion chosen by you to demonstrate the occurrence of Ca II components not found in neutral hydrogen are complex systems quite possibly immersed in extended atmospheres or gaseous streams. These streams may be the origin of some of the Ca II components. The star θ^1 Ori C (your Figure 12) is a likely case.

H. van Woerden: Ca II components arising in such extended atmospheres or gas streams would be circumstellar rather than interstellar. The term 'circumstellar' has, however, also been used in conjunction with the components with high negative velocities discussed by Schlüter *et al.* (1953). The sharp component at $V = -15$ km/sec in the spectrum of ι Ori is an obvious candidate for this category. The distinction between 'circumstellar' and 'interstellar' appears to me a matter of definition. A check on the interstellar character of the Ca II components is sometimes possible by comparison of spectra of stars close together on the sky.

T. K. Menon: The presence of components of optical depth exceeding 0·5 in the absorption spectra of practically all radio sources suggests the existence of a large amount of hydrogen in the form of dense clouds all over the Galaxy. This is neglected in the usual analysis of emission line profiles.

Van Woerden: These 'black' clouds, if Professor Hoyle will allow me to use this term, are indeed not seen in emission; otherwise one would get flat-topped profiles, because of saturation. Obviously these clouds are very small, and possibly cold too. There must be quite a lot of gas in this state, which has been overlooked in the general determination of density distribution and gas mass in the Galaxy.

C. Heiles: Can you quote typical masses and sizes for your Gaussian components in Orion?

Van Woerden: The masses and sizes depend on the (unknown) cloud distance and may vary over a wide range. The cloud with $V \approx -10$ km/sec, which is easiest to recognize (Figs. 8, 9 and 11), has a size of about 30×50 pc (if at 450 pc distance) and a mass of a few thousand solar masses; but it may well be a foreground object of smaller size and mass.

J. M. Greenberg: Has any work been done on a relationship between the velocity dispersion of external motions and the size of clouds?

Van Woerden: Whipple (1948) has suggested that the clouds with smaller optical depths have a wider velocity distribution than the thicker clouds. I have no new information on this subject. Of course, the stronger absorptions found by Adams at velocities close to zero must have been at least partly due to the overlap of components crowding at the peak of the distribution $f(V_0 - \bar{V}_0)$.

Greenberg: In your analysis of line profiles into Gaussian components (Section 6), wide intense lines are represented by two neighbouring Gaussians of similar strength and dispersion. As the line narrows or as the two components approach each other, there appears a tendency for one to grow with respect to the other. Is this generally true? If so, is it a mathematical or a physical result?

Van Woerden: If two components with the same dispersion have the same velocity, the machine cannot distinguish them at all; they just become one. The little component on the side might, then, just represent a slight asymmetry in the velocity distribution which comes out as an extra component. It might also be physically significant, but this requires a closer look.

P. O. Lindblad: If two components are seriously blended, there seems to be a tendency for this type of machine programme for Gaussian analysis to decrease one component and increase the other.

Van Woerden: We have the same experience.

H. L. Helfer: As I understand it, the reduction procedure, faced with handling a true situation of two Gaussians with small central-velocity difference, may yield one Gaussian, with too large a dispersion. Is this true? If so, the distribution of the dispersions will be biased towards higher dispersions.

Van Woerden: You are quite correct. Kaper *et al.* (1966, Section 5.3) have shown that two Gaussians with small differences in both V_0 and σ are difficult to separate and will tend to be represented by one wider Gaussian.

M. P. Savedoff: The analysis is linear and neglects absorption by one cloud of radiation by another. Hence I believe the Gaussian representation is only a mathematical convenience and the details we are discussing now probably are not of physical significance.

Van Woerden: We convert our observed profiles into optical depth, in order to take account of self-absorption. However, in the conversion we have to use a fixed gas temperature; this assumption may be far from reality. As long as the optical depths are low, this affects the profile shapes only little.

Heiles: Is the density of neutal hydrogen distributed non-uniformly in both velocity and space, or distributed non-uniformly only in velocity?

Van Woerden: A non-uniform distribution in velocity must quickly develop into a non-uniform space distribution, or smoothed out to a uniform velocity distribution because the mean free path is short. The variations in the surface density of hydrogen also indicate that the hydrogen is distributed non-uniformly in space.

I.A.U. Symposium no. 31, 1967

2. COINCIDENT CALCIUM AND HYDROGEN INTERSTELLAR LINES

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ABSTRACT

Observation of the 21-cm line in the directions of 34 high-latitude stars shows narrow emission features in most cases; in 18, the velocities of calcium- and hydrogen-line components agree within 2·5 km/sec. From the frequency of such coincidences as a function of the distance of the stars, a layer thickness of 350 pc for the gas is derived.

Profiles of the 21-cm emission line have been obtained in the directions of 34 high-latitude stars in whose spectra Münch and Zirin (1961) and Münch and Unsöld (1962) have reported absorption lines of interstellar calcium. The 140-foot (43-m) telescope and 100-channel autocorrelation-function receiver of the National Radio Astronomy Observatory at Green Bank gave a frequency resolution of 6·25 kHz (1·3 km/sec), a receiver noise temperature of 300 °K and an integration time of 10 minutes per point. Twenty-seven of the profiles contain a total of 40 narrow emission features; their velocities, obtained with an estimated accuracy of 1·3 km/sec, are listed in Table 1. All of the profiles show 21-cm emission with antenna temperatures exceeding 2 °K; however, broad features or those not sufficiently isolated from other features to form a distinct maximum are not

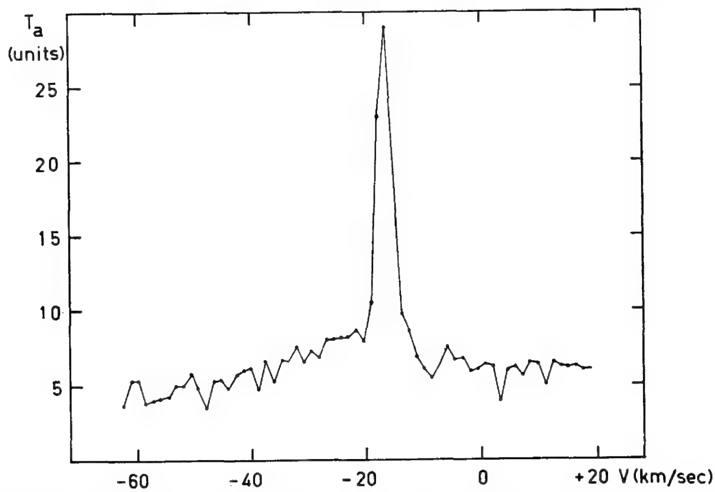

FIG. 1. The narrow emission feature in the 21-cm profile toward HD 156110. The integration time is 5 minutes for each point. The antenna-temperature scale is in units, which may depart by 25% from degrees Kelvin. The velocities are heliocentric.

Table 1

Comparison of hydrogen and calcium interstellar lines

Star HD	z (pc)	Heliocentric velocities of H I (km/sec)	Heliocentric velocities of Ca II (km/sec)	Intensity of Ca II
29 248	240	+23·2* +32·6	+2·5 +21·0*	1, 4
60 848	390	+15·9*	+13·4*	6
89 688	370	+4·2	+7·6	4
91 316	580	−8·5	−11·5 −2·0 +17·9	5, 2, 3
97 991	640	−5·5	+0·5	5
104 337	280	+0·2*	−0·5*	5b
119 608	2700	−9·2	−2·6 +18·5	5, 3
149 363	980	−14·2*	−12·6*	7b
149 881	890	−14·0*	−15·6*	9b
156 110	420	−17·0*	−38·7 −18·6*	1, 6
209 008	440	−17·4* −6·9	−16·8* −2·8	2, 2
212 571	230	−13·5* −4·9*	−14·1* −3·9*	7, 2
214 080	2000	−6·0*	−4·0* +16·6	6, 2b
214 930	490	−16·3 −10·0*	−10·9*	5
215 733	1200	−16·0 −9·7*	−57·0 −44·5 −25·8 −11·4*	2, 3, 4, 5
219 188	900	−9·2* −3·3	−28·9 −6·8* +17·8	2, 4, 1
220 172	710	−4·1*	−22·9 −2·2* +12·1	1, 4, 1
60 Her	19	−13·4	−27·3	
157 741	74	−20·2* −11·0	−20·9*	
158 148	102	−19·5*	−19·6*	
158 490	63	−18·4* −12·7 −4·8	−20·4*	
α Oph	7	−20·6 −14·6 −5·0	−26·1	
159 610	62	−15·6	−20·1	
159 735	67	−18·7* −7·0	−19·5*	
159 927	94	−17·2 −6·7	−20·5	
160 765	30	−17·3	−29·1	
95 Her	27	−15·7	−19·7	

* Indicates velocity difference between radio and optical lines $\leqslant 2{\cdot}5$ km/sec.

Note: Ca II data in the upper part of the table are from Münch and Zirin (1961), those in the lower part from Münch and Unsöld (1962).

included in Table 1. Figure 1 shows the spectrum measured in the direction of HD 156 110.

In eighteen cases the velocities obtained for 21-cm line components differ by 2·5 km/sec or less from the published velocities for calcium line components. The six strongest calcium components reported by Münch and Zirin (1961) all coincide (to an accuracy of 2·5 km/sec) with hydrogen features; and in the seven cases where a 21-cm feature coincides with one component of a multiple calcium line, it is always with the strongest calcium component. However, the correlation between the *strengths* of the coincident hydrogen and calcium lines is weak. For the 7 stars most distant from the galactic plane ($z > 700$ pc), which are least likely to have hydrogen emission beyond the star, there are 9 hydrogen features and 16 calcium components, of which 6 coincide.

We assume that hydrogen- and calcium-line components observed in the same direction

with velocities agreeing within 2·5 km/sec originate at the same distance. Since the calcium lines are formed between the Sun and stars of known distance, we are then able to investigate the distribution of the coincident hydrogen and calcium clouds perpendicular to the galactic plane. The distance, z, of a star above the galactic plane and the distance, r, from the Sun to the star are related by $z = r \sin b$, where b is the galactic latitude; the Sun is assumed to be located in the galactic plane. An effective path length to the star, which would be proportional to the number of coincident hydrogen and calcium clouds, is defined by

$$u = \int_0^z \rho(z)\,\mathrm{d}r, \tag{1}$$

where $\rho(z)$ is a dimensionless density function, independent of galactic longitude. The following equation results for the density function

$$\rho(z) = \frac{\mathrm{d}}{\mathrm{d}z}(u \sin b). \tag{2}$$

To derive $\rho(z)$ from the present observations, we classify the stars showing calcium components coincident with narrow 21-cm features into three groups according to the distance z. The first and second groups contain 9 stars each and the last contains 8. We omit star HD 119608, whose z-distance was listed as questionable by Münch and Zirin. For each star we obtain the value of $u \sin b$, by setting $u = 1$ for cases that have at least one pair of coincident lines and $u = 0$ for the remainder. For each group of stars, we derive average values $\langle u \sin b \rangle$ and $\langle |z| \rangle$, and list these in Table 2. We take the differences between adjoining entries in each column of Table 2, and use the fact that no coincidences can occur at $z = 0$. As an approximation to equation (2), the ratios of the differences in $\langle u \sin b \rangle$ and in $\langle |z| \rangle$ are the relative densities given in Table 3. The values of z in Table 3 are means between the adjacent values of $\langle |z| \rangle$ in Table 2.

Table 2

Average number of weighted coincident lines in three groups of stars

$\langle u \sin b \rangle$	$\langle \lvert z \rvert \rangle$ (pc)
0·136	49·2
0.481	329
0.516	988

Table 3

Relative density of coincident gas

Relative density	z-distance (pc)
276	25
123	190
5	660

If the density of coincident gas is zero beyond 660 pc and if the density at 25 pc is not exceeded, linear interpolation in Table 3 leads to a value of 350 pc for the z-distance between half-density points. This value may be compared with the determinations of 220 pc by Schmidt (1957) and 170 pc by Kerr (1964) for the thickness of the neutral-hydrogen layer between the Sun and the center of the Galaxy. We note that Van Rhijn (1946) obtained a value of 240 pc for the thickness of the calcium and sodium gas layer near the Sun.

The present method applies in the vicinity of the Sun, where the method used by Schmidt and by Kerr breaks down. In addition, the present method is independent of the distance scale derived from galactic rotation.

REFERENCES

Kerr, F. J. 1964, IAU Symposium, no. 20, *The Galaxy and the Magellanic Clouds*, Eds. F. J. Kerr and A. W. Rodgers, p. 81, Austr. Acad. Sci., Canberra.
Münch, G., Unsöld, A. 1962, *Astrophys. J.*, **135**, 711.
Münch, G., Zirin, H. 1961, *Astrophys J.*, **133**, 11.
Schmidt, M. 1957, *Bull. astr. Inst. Netherl.*, **13**, 247.
Van Rhijn, P. J. 1946, *Publ. Kapteyn astr. Lab.*, no. 50.

Discussion

Th. Schmidt-Kaler: I have obtained 21-cm profiles at the positions of most of the stars in front of which Münch and Unsöld found a very nearby cloud from the Ca II K-line absorption, and at additional positions. At all positions where Ca II is present in front of the stars, I find a 21-cm feature at the same velocity. In some positions (mostly at the edge of the region which seems to be covered by the cloud) an H I feature is seen although no Ca II has been observed. From Gaussian analysis as well as from the differences, observed minus expected profile, I derive a mean velocity $V_0 = -10{\cdot}3$ km/sec, a dispersion $\sigma = 3$ km/sec, and a peak brightness temperature of about 1 °K; the optical velocity is $-9{\cdot}7$ km/sec. This cloud is nearer than 15 pc.

There is another cloud at about 75 pc distance. It is well shown in our profiles, and even better in a series of profiles at $b = +30°$ obtained by Prof. Hachenberg. It appears to extend over about 12°. Its velocity is $-2{\cdot}1$ (optically $-2{\cdot}2$) km/sec, its dispersion 2·0 km/sec, its peak temperature about 8 °K.

From these measurements I have derived the dimensions l and densities n_H of the clouds. On comparison with the equivalent widths of Ca II, which yield the quantity $n_H^{\frac{3}{2}} l$, serious discrepancies arise in the sense that Ca must be underabundant (as noted already many years ago by Spitzer).

S. J. Goldstein: I observed all of the ten Münch-Unsöld stars whose spectra contained interstellar Ca II lines. All of these observations gave measurable hydrogen lines, but only four line components agreed with Ca II lines to an accuracy of 2·5 km/sec.

H. J. Habing: I do not see how you get reliable conclusions from your coincidence statistics, as long as you do not know what causes Ca II components to be absent in some cases and present in others. In my own observing program at Dwingeloo, I have found striking cases of non-coincidence; for instance, in HD 203 664 at $V = +70$ km/sec a very strong Ca II component is seen but no H I. Does a lack of understanding of such phenomena influence your results?

Goldstein: Whatever the causes of lack of coincidence (excluding the basic one, that the hydrogen is beyond the star), the present method is correct if the coincidences do not vary statistically with z distance. However, if the excitation of hydrogen or calcium lines varied with z in a way that reduced the number of coincidences, the gas layer would seem thinner than it is. For example, the kinetic temperature might increase with z. Then, the hydrogen atoms would be removed from the ground state while the calcium line still would be present. However, I selected for analysis only positions with accurately measurable hydrogen lines; so such an effect must be small. Since Münch and his collaborators undoubtedly selected stars with strong calcium lines, a similar argument applies to the converse case. Consequently, I think the method and the results are reliable. In the direction of the stars HD 203 664 and HD 93 521, I found no lines with accurately measurable velocity.

L. Spitzer: In connection with some of these remarks, I wish to point out that measurements of interstellar sodium lines would be of particular interest for those stars showing a coincidence between hydrogen and calcium components. The intensities of these three lines should then help to give information on the ionization conditions in different regions of the interstellar gas.

G. Westerhout: I do not understand why people are worried about the lack of coincidence between calcium and hydrogen lines. After all, we also observe a lack of coincidence between absorption and emission lines of hydrogen, and the cause is obvious: there are small features which show up in front of small radio sources, or, in the optical case, small stars. These may be high-density, small, perhaps cool objects, which when smeared over the wide radio beam disappear completely in the background. The calcium lines may come from just such features, which may well have lots of hydrogen in them, too.

C. Heiles: 21-cm absorption spectra can also be produced by big, cold clouds of large optical depth, which may not be observable in emission because of their low temperatures.

Westerhout: I just wanted to point out that the absence of correlation between calcium and hydrogen does not necessarily imply variations in the abundance ratio.

H. van Woerden: While the hydrogen layer thickness between half-peak intensity points is about 200 pc in the inner parts of the Galaxy, it appears to be about 500 pc around $R = 12$ kpc, as discussed in more detail elsewhere (Paper 23, and *Bull. astr. Inst. Netherl.*, in preparation). Consequently, it may be around 350 pc near the Sun, in excellent agreement with the result obtained by Goldstein. Nevertheless, I find Goldstein's method rather indirect and not very convincing.

Goldstein: Remember that this method yields a layer thickness, independent of the distance scale of the Galaxy and of velocity models.

M. P. Savedoff asks: Is there a bias in your analysis in that you find most of the gas concentrated near the plane but you assume that the representative point is at half the stellar distance?

Goldstein answers: The assumption that the gas occurs half-way to the star is unnecessary; the differential equation (2) gives the relative density directly. I am indebted for your question, since it has allowed me to remove an unnecessary assumption.

B. Strömgren: Observations in the optical wavelength range, in the direction of the north galactic pole, indicate very little reddening within 150 pc, while according to the observations made at Uppsala Observatory appreciable reddening sets in beyond 250 pc.

Van Woerden: These distance determinations of absorbing matter refer to only *half* the width of the layer; they suggest a thickness considerably greater than that found by Goldstein and by me for neutral hydrogen.

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3. IONIZED-HYDROGEN CLOUDS ASSOCIATED WITH YOUNG STELLAR CLUSTERS

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ABSTRACT

Observations of the 20-cm continuum with the 210-foot (64-m) Parkes telescope have furnished, for fifteen O-type clusters, the electron density and mass of associated ionized-hydrogen clouds.

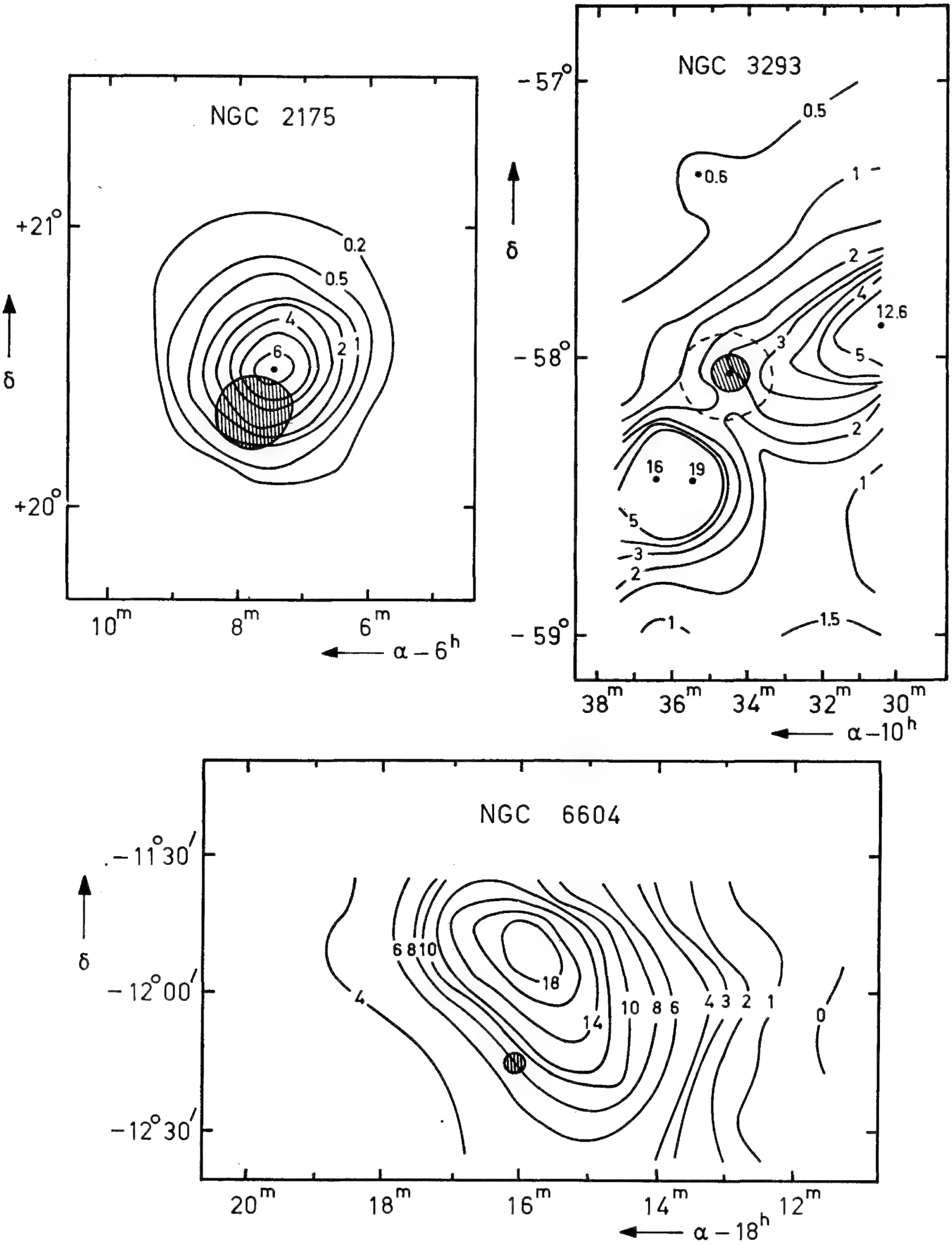
Knowledge of the total amount of gas associated with young stellar clusters is important in connection with hypotheses about their origin. The ages of very young clusters of type O, which are the nuclei of stellar associations, can not differ appreciably. If we assume the contraction theory of the origin of stars in clusters, the amount of remnant gas can be calculated. For clusters of similar age the relative contents of gas (i.e., the ratios M_{gas}/M_{stars}) must also be about the same.

In 1965, we have undertaken observations of fifteen O-type stellar clusters, using the 210-foot (64-m) steerable radio telescope of the Australian National Radio Astronomy Observatory at Parkes, Australia. We observed all clusters in the continuum at 20 cm, and with the 48-channel 21-cm line receiver described by McGee and Murray (1963). For some of the clusters, we also used a narrow-band receiver, with a bandwidth of 10 kHz = 2 km/sec.

The purpose of this paper is to give the preliminary results of the continuum observations, aiming at a determination of the amounts of ionized hydrogen in the clusters. The following objects were studied: NGC2175, 2264, 2353, 2362, 3293, 6167, 6193, 6204, 6231, 6383, 6514, 6531, 6604, 6611 and 6823. They were chosen to have angular dimensions comparable with the beamwidth of the telescope, which is 14′ (arc) at 21 cm, and to have known radial velocities from optical measurements. Knowledge of the radial velocities is necessary to ascertain the connection of the detected hydrogen clouds with the clusters under investigation. The reduction of line observations is not yet finished.

The observing procedure in the continuum consisted of a number of scans, mainly in declination, but sometimes in right ascension, over the region investigated. The scans were displaced from each other by 10′ (arc), and the area covered was about 10 times that of the clusters. In some complicated regions, additional scans in perpendicular directions were made as well.

The results of the observations are presented in contour diagrams of aerial temperature. Because the aim of our observations was a search for ionized-hydrogen clouds associated with the clusters, that is, a search for an excess of radiation in the direction of a cluster as compared with the background, the zeroes of the contour diagrams may be left arbitrary, and no measurements of the intensity of the background radiation were made. As examples the diagrams for NGC2175, 3293 and 6604 are shown in Figures 1–3.



FIGS. 1–3. Distribution of the continuum radiation at 20 cm wavelength in the regions around three O-type clusters. The contour values are excess aerial temperatures with respect to the surroundings of the cluster. The positions of the stellar clusters are indicated by shaded circles. Right ascension α and declination δ are for the equinox 1965.

In the case of NGC3293 the source of radio emission is indicated by a dashed circle; its position, diameter and brightness temperature were determined from individual scans, assuming a Gaussian distribution of the brightness and excluding the background radiation.

Inspection of the results obtained shows beyond doubt that ionized-hydrogen clouds are connected with the clusters NGC2264, 3293, 6231, 6514, 6531 and 6611. In the case of the clusters NGC2175, 6193, 6383 and 6823, the positions of the clouds detected do not coincide well enough with those of the clusters, and their relationships must be considered somewhat doubtful. The radio sources near NGC2362 and NGC6604 do not seem to be related with these clusters. The hydrogen-line observations will help to solve this problem definitely. No excess of radiation is found in the positions of NGC2353, 6167 and 6204.

The results of this investigation are summarized in Table 1, which gives the NGC numbers; adopted distances, D, as reported by Buscombe (1963); brightness temperatures, T_b, of the ionized-hydrogen clouds detected (doubtful cases are included), or the

Table 1

Ionized hydrogen in fifteen galactic clusters

NGC	D (kpc)	T_b (°K)	d (pc)	n_e (cm^{-3})	M ($M_\odot$)
2175	1·7	6·7	7·1	22·6	34
2264	0·8	0·5	6·4	6·9	7·7
2353	1·0	<0·2*	6·0**	<4·2	<3·8
2362	1·5	<0·2*	3·0**	<6·0	<0·7
3293	2·6	2·0	15	8·5	120
6167	—	<0·2*	—	—	—
6193	1·3	5·7	27·0	10	820
		5·4	3·5	36	6·5
6204	2·7	<0·2*	5**	<4·7	<2·4
6231	2·0	0·4	5·4	6·7	4·0
6383	1·2	3·7	5·7	19·0	13·5
6514	1·6	16·0	5·5	40	28
6531	1·2	1·6	5·6	12·5	9·0
6604	0·8	<0·6*	1·2**	<4·2	<0·03
6611	2·5	34·6	13	38	350
6823	2·2	2·9	16·5	10·0	200

* These upper limits are given in aerial temperature.
** Optical diameters.

upper limits of aerial temperature for undetected ones; diameters, d, of the clouds at half-peak intensity; electron densities, n_e; and the masses, M. In cases where no radiation was detected, we calculated upper limits on n_e and M, by adopting for the (hypothetical) clouds the optical diameters of the clusters. No distance estimate was available for NGC6167.

I wish to thank Dr E. G. Bowen and Mr J. G. Bolton for affording me the facilities of the ANRAO to make this investigation.

REFERENCES

Buscombe, W. 1963, *Mt. Stromlo Obs. Mimeogram*, no. 6.
McGee, R. X., Murray, J. D. 1963, *Proc. Instn. Radio Eng. Austr.*, **24**, 191.

Discussion

M. S. Roberts: How many of the open clusters studied have optical H II regions in their vicinity?

H. M. Tovmasjan: I have not had time yet to study the optical features, although I did consider these at the time of selection of clusters for observation. Some, but not all, of the clusters have nebulosity around them.

Mrs N. H. Dieter: One interesting possibility will be the comparison of your 21-cm observations in the clusters with the excited-hydrogen lines from the H II regions connected with the clusters. The velocities then will afford an additional parameter for correlation.

Tovmasjan: This comparison will definitely be made where possible. But I have not even commenced the analysis of the neutral-hydrogen observations.

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4. OBSERVATIONS OF NEUTRAL HYDROGEN IN OPEN CLUSTERS

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ABSTRACT

Neutral hydrogen is found in every young cluster observed, usually extending beyond the optical diameter, and in some cases showing expanding motions.

With the Bonn 25-m radio telescope (beamdwidth 33′, bandwidth 11·2 kHz = 2·4 km/sec, mean error of brightness temperature ± 0·5 °K), we have obtained 21-cm line profiles of twelve open clusters and their immediate surroundings. The arrangement of the positions of comparison profiles is shown in Figure 1. The expected profile we have calculated in two ways: from the profiles at positions at equal distances from the cluster centre, and from parabolic fits to series of profiles observed on diagonals through the cluster centre.

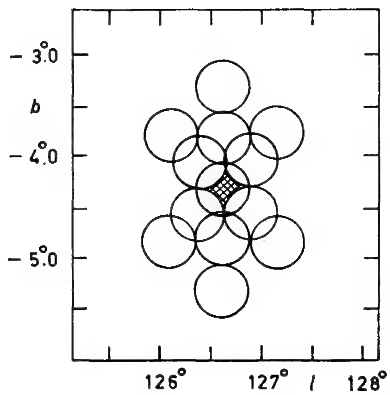

FIG. 1. Arrangement of the observed positions for NGC457. The cluster is at the centre (hatched). The diameter of the circles indicates the beamwidth.

Samples of the difference profiles (cluster minus surroundings) are displayed in Figure 2. Clearly, neutral hydrogen is present in NGC129, 457, and 869/884 (h and χ Persei). The optical velocities of the clusters, indicated by arrows, are within 5 to 10 km/sec

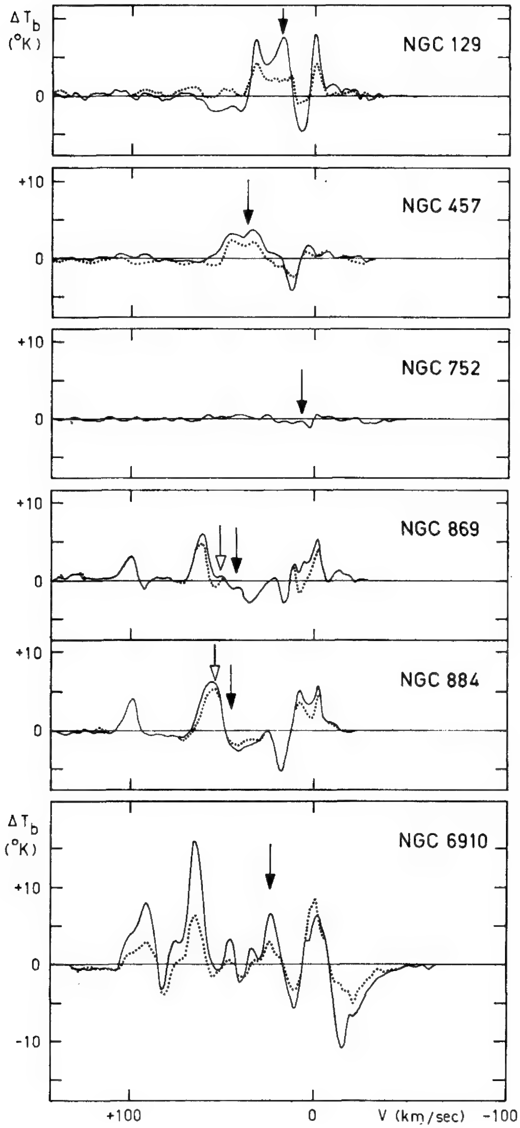

FIG. 2. Neutral-hydrogen emission of six open clusters. Differential 21-cm profiles are shown for the cluster positions, with respect to the surroundings. Dotted curves represent difference profiles obtained with the inner circle of comparison positions (cf. Figure 1); full-drawn curves indicate results with the more distant comparison profiles.

of the mean velocity of the hydrogen associated with the clusters. In some cases (e.g. NGC 129) there are indications of an expansion with a velocity of about 7 km/sec. On the average, the neutral hydrogen gas extends over a region whose size is about three times the optical diameter. In many cases a feature with a velocity near the local standard of rest is observed; this is due to small nearby clouds.

Figure 2 also shows the poorest case, NGC 6910. Which 21-cm feature, if any, corresponds to the cluster can here be decided only on the basis of the optical velocity. However, even in this case a prediction of the velocity using the photometric distance and galactic rotation would have been successful.

We have found neutral hydrogen to be present in all clusters with ages of 25 million years or less, although the picture is complicated in the case of O-type clusters; no cluster older than 150 million years contained detectable amounts of hydrogen. Details of this work will be published shortly (Schwartz 1967, Schmidt-Kaler and Schwartz 1967).

REFERENCES

Schmidt-Kaler, Th., Schwartz, R. 1967, *Z. Astrophys.*, in preparation.
Schwartz, R. 1967, Forschungsberichte des Landes Nordrhein—Westfalen, no. 1844.

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5. OBSERVATIONS OF THE SPATIAL STRUCTURE OF INTERSTELLAR HYDROGEN

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ABSTRACT

High-resolution 21-cm line observations in a region around $l^{\mathrm{II}} = 120°$, $b^{\mathrm{II}} = +15°$, have revealed four types of structure in the interstellar hydrogen: a smooth background, large sheets of density 2 atoms cm^{-3}, clouds occurring mostly in groups, and 'cloudlets' of a few solar masses and a few parsecs in size; the velocity dispersion in the cloudlets is only 1 km/sec. Strong temperature variations in the gas are in evidence.

The 21-cm line radiation emitted by low-velocity neutral hydrogen has been mapped in detail in the region bounded by $l^{\mathrm{II}} \approx 100°$ and $140°$, $b^{\mathrm{II}} \approx +13°$ and $+17°$, with the 300-foot (91·4-m) telescope and the 100-channel autocorrelation receiver at the National Radio Astronomy Observatory in Green Bank. The beamwidth of the antenna at this wavelength is 10 minutes of arc, the velocity resolution about 1 km/sec, the total range of velocities observed about 50 km/sec, and the antenna-temperature sensitivity about 1 °K.

The adoption of a common distance of 500 pc to all of the hydrogen is a reasonable approximation; little hydrogen appears to exist in the vicinity of the Sun in this region. The gas can be resolved into three physical components: a diffuse smooth background, contributing about two thirds of the integrated 21-cm emission; and two large sheets of gas, in which the hydrogen density is probably about 2 atoms/cm^3, and which contain structure. These sheets have relative motion; the velocity of each is highly ordered over distances of tens of degrees on the sky; linear structures characterized by the absence of hydrogen ('rifts') run across each sheet. In part of the region the sheets coexist in space and velocity.

The present observations do not agree at all with the predictions of the 'standard cloud model'. Concentrations of gas which one might call clouds are present in the sheets, but usually their density is no larger than twice that in the surroundings; about ten of these objects are found in the region, some of which are so large that the tidal force of the galactic gravitational field must affect their equilibrium. Especially prominent are the 'group clouds', which are similar to classical 'interstellar clouds' but are clumped together into two groups; much of the large velocity dispersion of these objects may result from systematic radial motions within each group. No enhanced 21-cm emission is observed at positions of dense dust clouds; this is attributed to the presence of cold or molecular hydrogen in these objects, which are probably bound by self-gravitation.

Small concentrations of near stellar mass, distinctly different from the above concentrations, are observed in profusion; but since they are small they contain only about

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10% of the mass of the sheets. Typical radii of these 'cloudlets' are a few parsecs; excess densities are not large, about a factor two. The upper limit to their kinetic temperature implied by their velocity width is about 100 °K.

The highest brightness temperature observed in the region is 130 °K, roughly equal to the commonly-accepted harmonic mean value for the kinetic temperature in the galactic plane; the line profile at the position of this intensity maximum does not appear saturated. This, together with the observation of dust clouds in which no excess 21-cm radiation is visible, implies the existence of large temperature variations in the interstellar gas.

The decrease of N_H, the number of hydrogen atoms per column of 1 cm^2 cross-section, with increasing galactic latitude b is much faster than that of $1/\sin b$; the decrease near latitude 28° is almost discontinuous. The conclusion follows that in this region little hydrogen exists in the neighbourhood of the Sun.

A complete report of this work is in preparation (Heiles 1967).

REFERENCE

Heiles, C. 1967, *Astrophys. J.*, in preparation.

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6. THE TEMPERATURE OF GALACTIC NEUTRAL HYDROGEN

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ABSTRACT

There appears to be no correlation of the velocity dispersion of Gaussian components observed in 21-cm absorption profiles with the angular diameter of the radio source. Consequently, the difference of typical dispersions observed in absorption and in emission must be due to excitation temperature fluctuations. A hot medium of 600 °K is postulated.

It is well known that 21-cm absorption spectra are much more strongly peaked than emission spectra. The median dispersions obtained in analyses of 21-cm profiles into Gaussian components may be used to specify this property quantitatively. Typical dispersions σ obtained for neutral-hydrogen profiles near the galactic plane are: 6 kHz in absorption (Clark 1965), 20 kHz in emission (Lindblad 1966). The difference between these values is usually attributed to: (*a*) differences of angular resolution; (*b*) different weighting of excitation temperature fluctuations.

If (*a*) alone applied, one would expect that a plot of the dispersions of the Gaussian components in absorption profiles vs the angular diameters of the radio sources observed would show a smooth increase, from 6 kHz for point sources to 20 kHz for H II regions

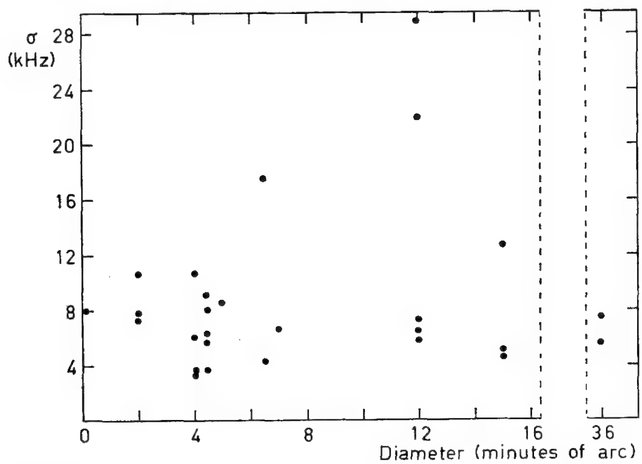

FIG. 1. A plot of the dispersions σ of Gaussian components in 21-cm absorption profiles (Clark 1965) versus the angular diameters of the radio sources observed.

*Presented by C. H. Costain.

with angular dimensions comparable with the beamwidths of antennas normally used to obtain emission profiles. Figure 1 shows such a plot using the results of Clark, who analysed absorption profiles obtained with the Owens Valley interferometer into Gaussian components. Only components with centre frequencies (velocities) within 50 kHz (10 km/sec) of the local standard of rest (i.e., due to nearby hydrogen) have been plotted. The main feature of the plot is that the dispersions tend to cluster around 6 kHz, *irrespective of the angular diameter of the radio source observed.* These data, based on 13 profiles, suggest that the stronger peakedness of absorption profiles is *not* due to the greater angular resolving power normally obtained in absorption studies.

If one then assumes that the difference of typical dispersions is due to temperature fluctuations, the range of temperatures normally accepted (40 to 140 °K) is insufficient to account for the marked differences in the appearance of absorption and emission profiles. Therefore, it seems very likely that there is an additional factor operating, which either smooths emission or sharpens absorption profiles. Clark (1965) has suggested that this additional factor is a hot continuum of neutral hydrogen (excitation temperature $\geqslant$ 1000 °K), which is invisible in absorption profiles, but contributes appreciably to emission profiles. The author believes that this view is essentially correct, but would suggest from the available observational data (e.g. Muller's (1959) absorption profiles of Cygnus A, and the estimate by Dieter and Goss (1966) of the thermal broadening of high-latitude emission profiles) that the temperature of the hot medium is about 600 °K.

REFERENCES

Clark, B. G. 1965, *Astrophys. J.*, **142**, 1398.
Dieter, N. H., Goss, W. M. 1966, *Rev. mod. Phys.*, **38**, 256.
Lindblad, P. O. 1966, *Bull. astr. Inst. Netherl. Suppl. Ser.*, **1**, 177.
Muller, C. A. 1959, IAU Symposium no. 9, *Paris Symposium on Radio Astronomy*, Ed. R. N. Bracewell, Stanford University Press, Stanford, U.S.A., p. 360.

I.A.U. Symposium no. 31, 1967

Chapter I B

Interstellar Molecules

CHAIRMAN: G. Herzberg

(*Division of Pure Physics, National Research Council, Ottawa 2, Canada*)

'Someone out in interstellar space was obviously signalling at one of our participants.'

G. R. Burbidge, at the closing dinner

7. RADIO OBSERVATIONS OF INTERSTELLAR MOLECULES

(Introductory Report)

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ABSTRACT

Investigations of the 18-cm lines of the $^{16}O^{1}H$ radical are still in an exploratory phase. The detection of the strongest line of the $^{18}O^{1}H$ radical has just been reported. Searches for the microwave lines of CH and SiH are in progress.

OH absorption has been observed for a few of the stronger radio sources, for a dozen galactic H II regions and for the source complex at the galactic centre. The ratio τ_{OH}/τ_{H} varies by three orders of magnitude between these sources. In most cases the intensity ratios for the four OH lines are anomalous, which indicates that the populations of the energy levels are perturbed.

No thermal emission from OH has been found, even where $\tau \approx 1$. It thus becomes exceedingly difficult to estimate excitation temperatures and to derive surface densities.

Strong non-thermal emission is seen from about a third of the H II regions observed. The line profiles are composed of many narrow spikes, quite different for each of the four lines. The intensity ratios of the emission peaks are highly anomalous. The OH emission comes from exceedingly small areas ($< 0{\cdot}1$ pc) on the *edge* of the ionized regions, with brightness temperatures higher than 10^{6} °K.

It has been suggested that the populations are inverted. Maser amplification of the background continuum then occurs. Power gains of 10^{4} to 10^{5} are required. To produce such a gain in a very small region would require high OH densities and a considerable degree of population inversion.

In at least eight sources the emission is highly polarized. Complete circular polarization is common, and the sense varies rapidly between adjacent spikes in the profile. The observed polarization is incompatible with Zeeman multiplets.

1. INTRODUCTION

The study of interstellar molecules by means of their radio-frequency spectrum is still in its infancy. The 18-cm lines of the $^{16}O^{1}H$ radical were first observed less than three years ago, and the investigations are still in an exploratory phase. The detection of the strongest line of the $^{18}O^{1}H$ radical was reported only a month ago, in July 1966. Searches for the microwave lines of CH and SiH are in progress, with great secrecy surrounding the expected transition frequencies.

By contrast with the 21-cm work on neutral atomic hydrogen, our theoretical background has proved to be quite inadequate for the OH observations at 18 cm. So many surprising, and baffling, discoveries have been made that we expect yet more to come. We still have little idea how to account for the high molecular densities, for the great variability of the abundance of hydroxyl molecules relative to hydrogen atoms, for the formation of OH in regions where the atoms themselves are ionized, for the processes exciting the energy states, or for the mechanisms which produce polarized, non-thermal radiation with, perhaps, rapid temporal variations.

2. LAMBDA-DOUBLING IN OH

The ground state of the OH molecule is split by lambda-doubling, an interaction between the rotation of the nuclei and the motion of the unpaired electron in its orbit. Each level has also a small hyperfine splitting. The electron and spin configurations are shown in Figure 1, with the energy levels on the right of the diagram.

Transition *a-c* at 1667·358 MHz is nine times as probable as *b-c* or *a-d*, and nearly twice as probable as *b-d* at 1665·401 MHz. These are electric-dipole transitions, about ten thousand times stronger than the magnetic-dipole transition producing the 21-cm line. It thus becomes possible to detect radio lines from molecules at concentrations below 10^{-7} per cm^3, commensurate with the molecular densities observed by means of optical interstellar absorption lines.

3. OH IN ABSORPTION

The frequencies of the two main Λ-doubling lines of OH were measured at Columbia University seven years ago (Ehrenstein *et al.* 1959), but it was not until four years later that the MIT group (Weinreb *et al.* 1963) observed them in absorption in the spectrum of Cassiopeia A. The largest absorption measured was 1·6% at 1667 MHz, and about 1% at 1665 MHz. Later measurements (see, e.g., Rogers and Barrett, Paper 11 in this volume) have confirmed that in Cas A the intensity ratio of these two lines is close to the theoretical and laboratory ratio of 9:5. Close correspondence of the velocities of the absorption features with those at 21 cm showed that the OH occurred in neutral-hydrogen clouds. However, the ratio τ_{OH}/τ_{H} appeared to vary from cloud to cloud. At that time it seemed to be straightforward to write:

$$\tau_{OH} = \frac{h\,c^2 A}{8\pi k\,\nu_0\,\Delta\nu}\cdot\frac{g_i}{\Sigma g_i}\cdot\frac{N_{OH}}{T_s}\;, \tag{1}$$

and only a determination of the excitation temperature T_s was required to allow a calculation of the surface density N_{OH}. Any OH seen in directions away from Cas A should produce an emission line of brightness temperature $\tau . T_s$. No emission could be

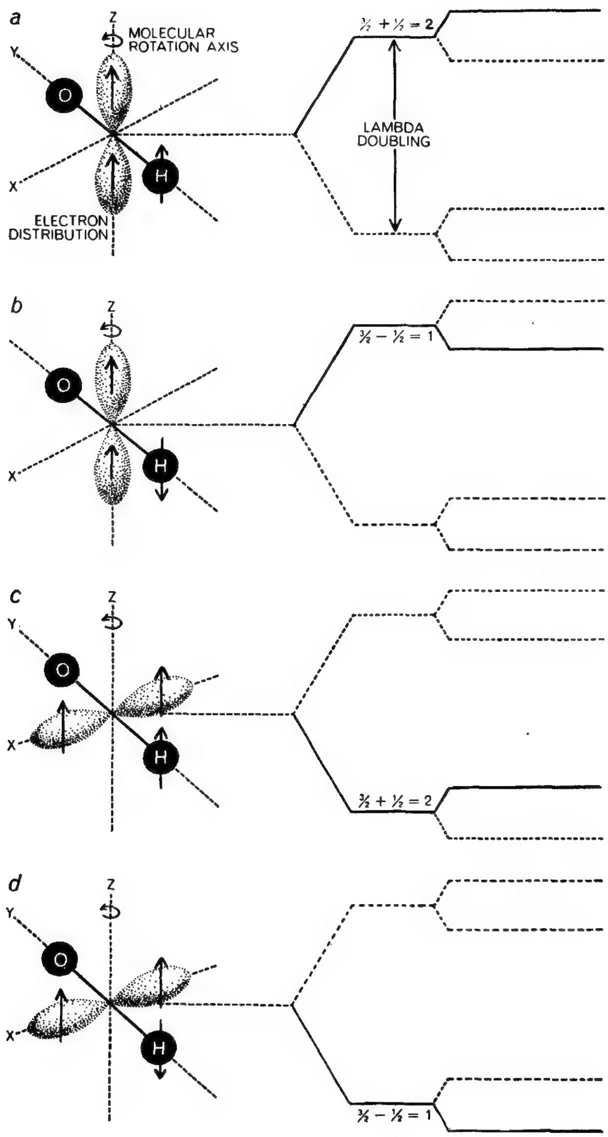

FIG. 1. Electron and spin configurations for lambda-doubling and hyperfine splitting of the $^2\Pi_{3/2}$, $\mathcal{J} = 3/2$ state of the OH molecule (Barrett 1964). The four corresponding energy levels are shown on the right.

detected, and Weinreb *et al.* (1963) assumed an upper limit of 10 °K for the excitation temperature. This gave an estimated abundance ratio N_{OH}/N_H of the order of 1×10^{-7}.

A month after the MIT observations, absorption features in the spectrum of Sagittarius A were found at 1665 and 1667 MHz by Bolton *et al.* (1964*a*), and at 1667 MHz by Dieter and Ewen (1964) and by Weaver and Williams (1964). The observations were made near zero radial velocity, and appeared to correspond to the absorption at 21 cm. However, more extensive observations at Parkes (Robinson *et al.* 1964, Bolton *et al.* 1964*b*) and Harvard (Goldstein *et al.* 1964) revealed that the OH absorption of Sgr A is dominated by two strong features which correspond to low-intensity wings of the 21-cm profile (Figure 2). For the strong feature at +40 km/sec the optical depth is close to unity, although the line is very broad. But still no emission could be seen to allow a separation of N_{OH} and T_s. If T_s were the same as assumed for the spiral arms in front of Cas A, the ratio N_{OH}/N_H for the strongest OH absorption in Sgr A would be equal to 10^{-4}. Since the normal abundance of oxygen relative to hydrogen is $6{\cdot}7 \times 10^{-4}$, a large proportion of the oxygen atoms should then have formed molecules. As we know of no efficient process for producing OH (cf. Salpeter, Paper 8), we are forced to the conclusion that, for the OH in front of Sgr A, T_s must be much lower than the 10 °K assumed above

For Sgr A the intensity ratio of the 1665- and 1667-MHz lines was not the expected 5:9; Robinson *et al.* (1964) found it to be 5:6. This could have been explained by an optical depth of about 2·7, but there is no saturation—the intensity ratio stays constant right down the skirts of the profile.

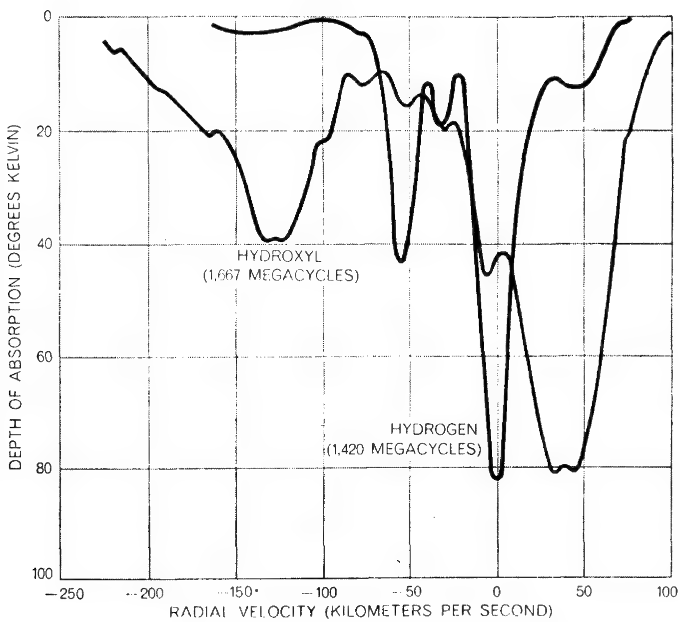

FIG. 2. Absorption spectra of Sagittarius A at 1420 and 1667 MHz observed with the Parkes 210-foot (64-m) telescope. The intensity scale refers to the OH line at 1667 MHz only. (Bolton *et al.* 1964*b*; reproduced from Robinson 1965)

4. SATELLITE LINES

The strong absorption of Sgr A led us to search for the satellite OH lines, whose frequencies had been computed to ±2 MHz. We easily found (Gardner *et al.* 1964) the lower-frequency satellite line at 1612·231 MHz—more than a factor of 3 stronger than anticipated. An optical depth of 3·5 at 1667 MHz might have explained this, had it been consistent with the measured depth of absorption and with the 1665/1667 intensity ratio. The higher-frequency satellite line at 1720·53 MHz was detected at the same time (with the use of makeshift equipment). Its intensity appeared to be similar to that at 1612 MHz. It was a year later before we measured it accurately. Then, to our surprise, we found (McGee *et al.* 1965) that it had only 70% of the strength of its twin line! In the spectrum of Sgr A the intensity ratios for the +40 km/sec feature are 1·4:2·7:3·3:1. Radford (1964) had, in the meantime, measured the satellites in the laboratory and found the expected ratios of 1:5:9:1. The inequality observed for the intensity of the satellites shows that the populations of the energy levels are perturbed by some unknown mechanism from their Boltzmann ratios, whatever the optical depth. In other parts of the galactic-centre region we have found very different intensity ratios, as shown in Table 1. Nowhere do we find the expected ratio. The closest is 1:3:6:1 in the negative-velocity absorption of Sgr A.

Table 1

Normalized Intensity Ratios for OH Absorption

l^{II}	b^{II}	Cloud Velocity	1612 MHz	1665 MHz	1667 MHz	1720 MHz
Theoretical ratio		—	1	5	9	1
0°	0°	+45 km/sec	1·5	3·2	3·4	1
0°	−0° 10′	+40 km/sec	2·0	3·0	3·4	1
0°	0°	0 km/sec	2·2	5·6	7·2	1
0°	−0° 10′	+ 8 km/sec	3·0	5·8	7·3	1
0° 30′	0°	+24 km/sec	0·6	1·6	2·1	1
0° 40′	0°	−85 km/sec	0·7	1·8	2·6	1
0° 40′	−0° 10′	−94 km/sec	0·5	1·7	2·3	1
0° 40′	−0° 10′	+60 km/sec	1·1	2·4	2·2	1
Sgr A		+42 km/sec	1·4	2·7	3·3	1

5. SMALL-SCALE DISTRIBUTION OF OH ABSORPTION

The absorbing OH is located in H I regions. Absorption has been observed in a dozen sources close to the galactic plane, and the velocities generally agree closely with those of the 21-cm absorption profile (where available). However, the ratio τ_{OH}/τ_{H} varies widely from cloud to cloud. No absorption was detected in strong sources such as Taurus A, Orion A, and Virgo A, which all have marked 21-cm absorption.

Our only information on the sizes of the OH clouds comes from the galactic-centre region, where we see the absorption projected on the extended continuum-source complex. The hydrogen covers the whole region, with the OH concentrations embedded in the neutral hydrogen (Bolton *et al.* 1964*b*). The distribution of the opacity of the gas with

velocities of $+57$, -95 and -135 km/sec is shown in Figure 3 by the heavy contours. The fine lines are the contours of the continuum emission from the Sgr-A complex. The gas at each velocity appears to be disposed in 'clouds' with typical dimensions of 15′ (arc), or 50 pc; these would be comparable with the sizes of clouds of neutral hydrogen, but the dimensions found are strongly affected by the angular resolution of the telescope.

There are more than a dozen such OH complexes in the central regions. There is a considerable amount of overlap in the line of sight. The OH clouds lie preferentially south of the galactic plane.

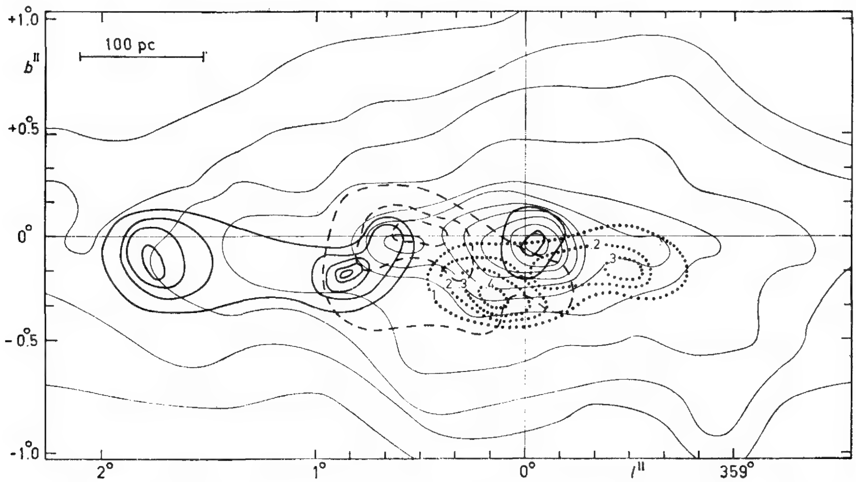

FIG. 3. Distribution of opacity in the 1667-MHz OH line, in the region of the galactic centre. The fine contours refer to the continuum at 1660 MHz. The other contours show OH opacities (contour interval 0·1) at three typical velocities: -135 km/sec (dotted), -95 km/sec (dashed), and $+57$ km/sec (solid line). Observations made with the Parkes 210-foot telescope, beamwidth 0°20 at 1667 MHz. (Robinson 1965)

6. OH EMISSION

After the initial observations of OH absorption in the spectra of Cas A and Sgr A, and the failure to detect absorption in front of the other strong sources, the search for OH in other parts of the Galaxy was continued by the groups at Berkeley and Harvard, with 85- and 60-foot (26- and 18-m) telescopes but adequate amounts of observing time. They, too, had no success with absorption observations of the strongest radio sources; nor could any OH emission be found in the spiral arms (Penzias 1964).

The search was continued, with marginal success, through the weaker galactic sources, mainly H II regions. W49 provided the first fireworks; OH appeared here not in absorption, but in emission against the continuum background (Gundermann 1965, Weaver *et al.* 1965). Confirmatory observations were made at 1665 MHz where, to increase the confusion, the emission was found to be still stronger. The line profiles were composed of many narrow spikes (Weaver *et al.* 1965, Zuckerman *et al.* 1965), and the 1665/1667 intensity ratio varied enormously from spike to spike, so that the profiles appeared

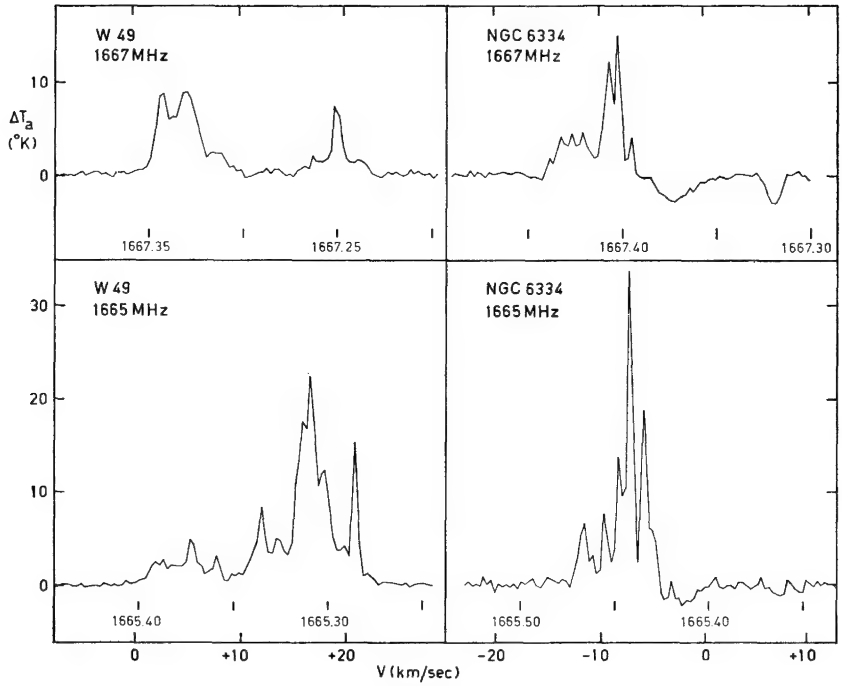

FIG. 4. Initial observations of OH emission at 1665 and 1667 MHz from near W 49 and NGC 6334. Velocity scale is with respect to the local standard of rest; intensities shown in °K of antenna temperature. Observations with Hat Creek 85-foot (26-m) telescope, receiver bandwidth 2 kHz. (Weaver *et al.* 1965)

completely different for the two lines (Figure 4). Similar emission was found in W3, W51, W75, NGC6334 and Ori A. The Berkeley group proposed an unidentified line of 'mysterium' to explain the excess emission at 1665 MHz. However, at MIT Weinreb *et al.* (1965) found emission at 1720 MHz for W3, while the Australian group (McGee *et al.* 1965) observed emission at 1612 and 1720 MHz in a number of sources. In W49 the line-intensity ratios for the two major peaks are 1:23:0:1·5 and 1:6:11:0·4 (Figure 5). The absorption measurements had already prepared us for very anomalous intensity ratios, and it was clear that the narrow emission spikes came from OH molecules with highly perturbed populations of the energy levels.

OH emission has been found in 12 of the 35 H II regions observed. In some of these (W51, NGC6334) absorption is also seen (Figure 6), while seven show absorption only. In the case of NGC6334 we have established that the absorption is not associated with the nebula but with a nearer H I region. The absorption velocities agree with those seen at 21 cm, and also with the OH absorption of the nearby nebula NGC6357 (which has no anomalous emission). However, the line-intensity ratios for the absorption are abnormal, particularly for the satellite lines.

McGee *et al.* (1965) could not resolve the emitting sources in W49 and NGC6334 with the 12′ (arc) beam of the Parkes telescope, so that the source diameter was under 5′

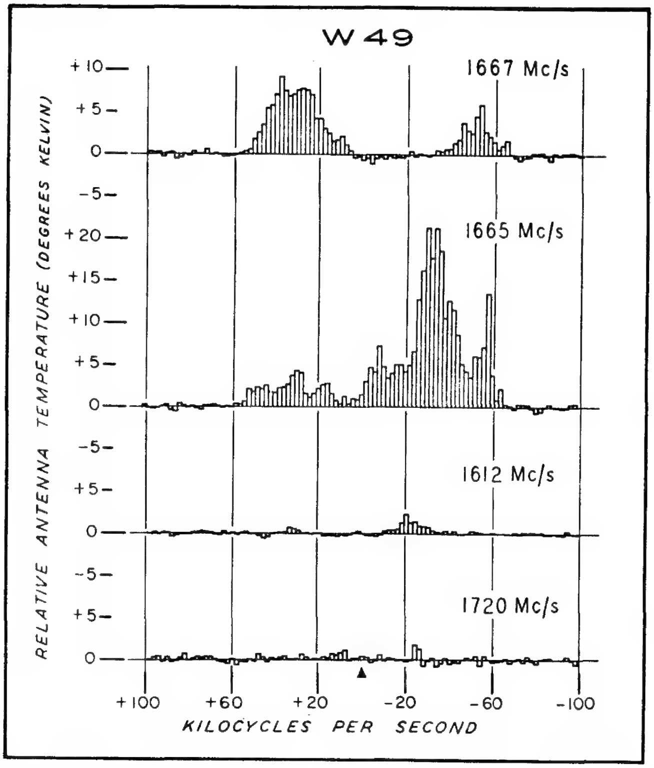

FIG. 5. Emission spectra for all four OH lines from W 49, as observed with the Hat Creek 85-foot telescope and 2 kHz bandwidth. The ratios of the intensities of the lines vary widely for the different components of the spectrum. (Reproduced from Dieter *et al.* 1966)

(arc). The 1665-MHz antenna temperature for W49 was 150 °K, so that its brightness temperature must exceed 1000 °K. Quite recently the groups at MIT (Rogers *et al.* 1966; Burke *et al.*, Paper 9 in this volume) and CalTech (Cudaback *et al.* 1966) have tried to resolve the sources in W3, W49, NGC6334 and Sgr B2, using interferometers. We discuss their results in detail in Section 8. In general, the sources are found to be smaller than 20″ (arc), and for the strongest components the brightness temperature exceeds 10^6 °K. This contrasts strangely with the narrowness of the spikes, whose Doppler width of 1 kHz (0·2 km/sec) or so would correspond to a kinetic temperature of less than 20 °K. Moreover, such narrow lines are most unexpected in or near H II regions with a temperature of 10^4 °K and turbulent velocities of 5 to 10 km/sec.

7. POLARIZATION

The MIT observers have studied W3 in detail and found, most surprisingly, that the OH emission is polarized. They first observed (Figure 7) that some of the emission at 1665 MHz was 38% linearly polarized (Weinreb *et al.* 1965). There are a number of mechanisms which could produce such polarization, but the Zeeman effect appeared

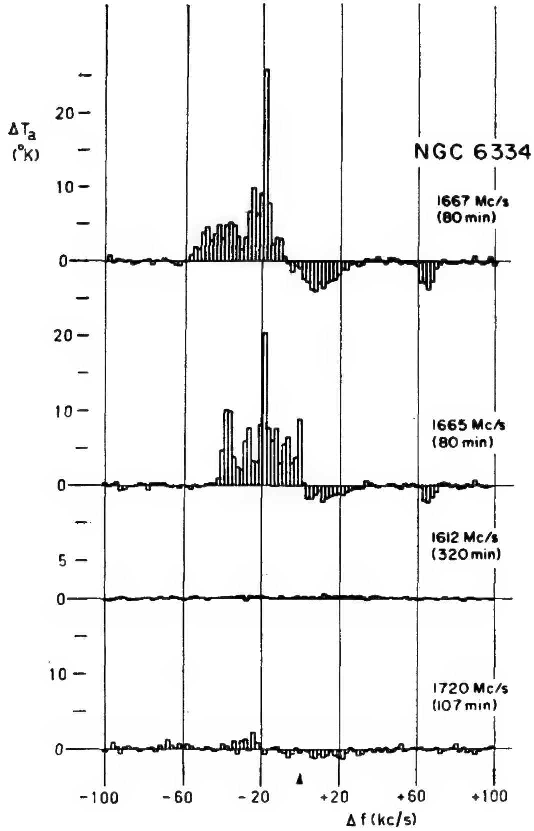

FIG. 6. Spectra for all four OH lines from NGC 6334, showing two absorption features to the right of the emission profile. The absorptions at 1612 and 1720 MHz are markedly anomalous. (Hat Creek 85-foot telescope, 2 kHz bandwidth)

unique among these as the only mechanism which would also give rise to circular polarization. Barrett and Rogers (1966) immediately looked for circular polarization in W3, W49, NGC6334 and Sgr B2, and found that some components were 100% circularly polarized (Figure 8). Similar results were obtained at the same time at Jodrell Bank (Davies *et al.* 1966). However, the observed polarization cannot be readily understood in terms of Zeeman patterns.

Figure 8 shows that at 1665 MHz there is no obvious pairing of the lines, and the left-hand and right-hand components have widely different intensities. If one attempts to find Zeeman patterns in the profiles (Davies *et al.* 1966), one must invoke fields of the order of 5×10^{-3} gauss. But how does one then explain the 1612-MHz profiles in W3, where there is a *single* line of right-hand circular polarization instead of a Zeeman multiplet of six components?

Mainly circular polarization has also been found in the sources W49, Ori A, NGC6334,

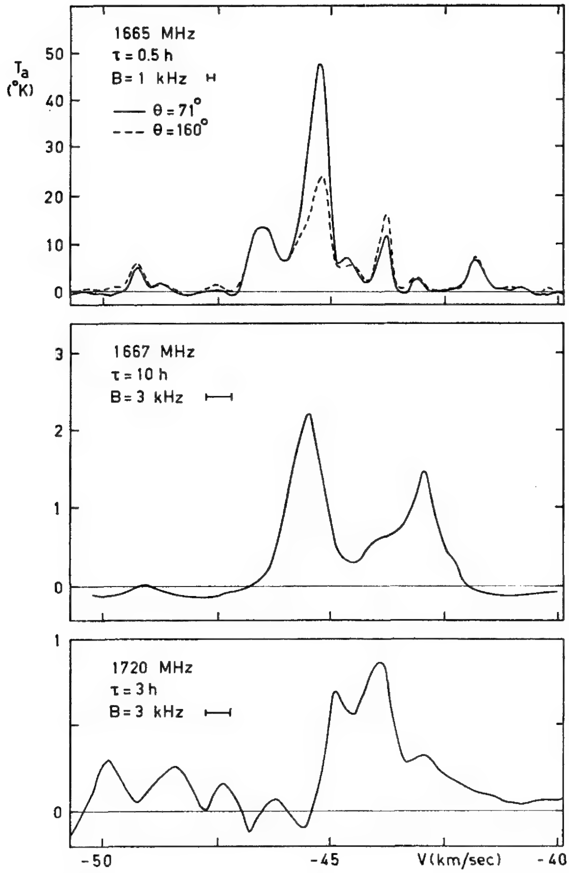

FIG. 7. OH emission from W3 at 1665, 1667 and 1720 MHz. The intensity scales are different for the three lines; so are the bandwidths B and integration times τ. At 1665 MHz measurements with two orthogonal feed position angles, θ, reveal up to 38% linear polarization. (Weinreb *et al.* 1965)

Sgr B2, RCW74, 1617−50 and MHR49. The Berkeley observers have found (Dieter *et al.* 1966) up to 90% linear polarization in NGC6334, but in our own observations we have seen no linear components (with a limit of 5%).

8. LOCATION OF THE OH EMISSION

The largest of the H II regions emitting OH lines is NGC6334, with optical dimensions of 40′ × 30′; it consists of three distinct H II regions, crossed by heavy obscuration (Figure 9). It is well resolved with the 12′ beam of the Parkes telescope, and we have investigated the emission in detail (Gardner *et al.* 1967). There are three major emission peaks, at velocities near +7, +10 and +13 km/sec. All three emissions are found to come from a point source at A, on the *edge* of the upper of the three H II regions. Interferometry (Rogers *et al.* 1967) shows that the positions of all spectral components coincide

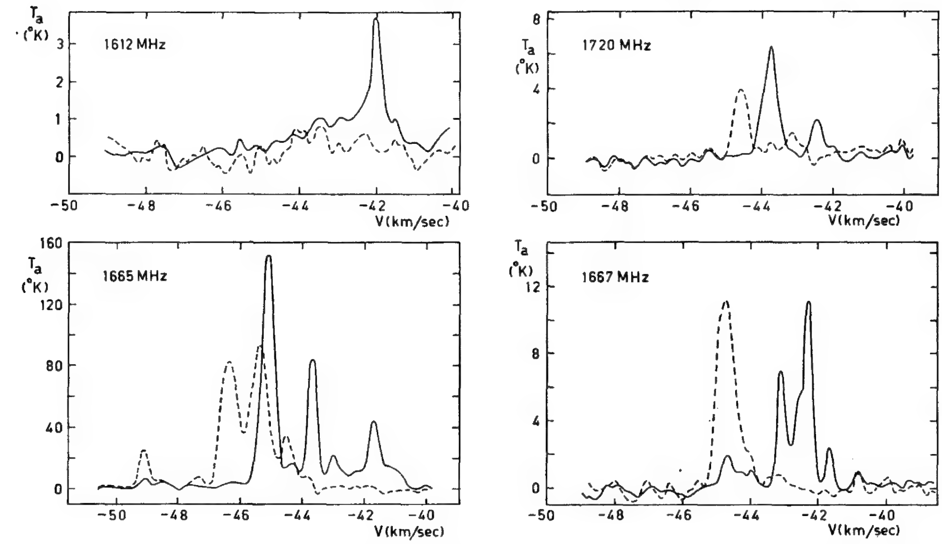

FIG. 8. Observations of OH emission from near W 3 with right-hand (solid line) and left-hand (dashed line) circular polarization. The intensity scales are different for each frequency. Observations made with the Green Bank 140-foot (43-m) telescope and 1·25 kHz = 0·225 km/sec bandwidth. (Adapted from Barrett and Rogers 1966)

to within 7″ (arc). Emission at a similar group of velocities also comes from a point source at B, between two of the H II regions. Source A is strongest at 1665 MHz, while source B is stronger at 1667 MHz; this is rather reminiscent of the two main components in the spectrum of W49. At each velocity the two sources in NGC6334 are highly circularly polarized, in opposite senses.

For W49, interferometer measurements (Cudaback *et al.* 1966; Burke *et al.*, Paper 9; Rogers *et al.* 1967) show again two point sources, spaced by 2′ (arc), lying adjacent to the two parts of the continuum source. For each source the positions of each spectral component at 1665 and 1667 MHz agree to better than 7″ (arc). One source is stronger at 1667 MHz, the other at 1665 MHz.

In W3 and Sgr B2 there is only a single point source, all spectral components coming from positions coincident to within 3″ (arc) and 7″, respectively. The OH source in W3 lies well south of the nebulosity IC1795 in a region of heavy obscuration. Mezger (private communication) has detected, at 2 cm wavelength, a very weak continuum source near this position.

9. TEMPORAL VARIATIONS

The Berkeley observers (Dieter *et al.* 1966; see also Paper 10) have reported that in NGC6334 and Ori A the intensity of the emission changes with time. Over a 3-month interval the profiles of NGC6334 at 1665 and 1667 MHz changed markedly, by as much as a factor of ten. Individual features within the profiles appeared to vary independently of adjacent ones.

Closer examination suggested that the variations have a period as short as ten days. On a light-travel-time argument the size of these sources can then be no larger than 0·01 pc. This would increase our estimate of the brightness temperature by another factor of a hundred.

Most other groups have been observing only sporadically, and can only say that no long-term changes have been noted. We have seen no change in the profile for source A of NGC6334 (cf. Figure 9) in observations spread over 6 months, or in Sgr B2 in observations over 18 months.

10. MECHANISM OF THE EMISSION

It is most unlikely that we are seeing spontaneous emission by OH. The curious polarization of the lines rules out any normal thermal mechanism—as do the high brightness temperatures. The emission shows only when there is a bright source behind, which should lead to absorption unless the excitation temperature, T_s, exceeds the brightness temperature of the background. Thermal emission would require a high value of T_s *plus* a large optical depth. Since $\tau \propto N_{OH}/T_s$, this implies enormous densities. The lines would also have to be much broader than is observed.

The best alternative explanation offered is that the energy states are perturbed enough to invert the populations. Maser amplification of the continuum background can then occur. The power gain required is at least 10^5, which will produce a narrowing of the natural linewidth by a factor of about 5. The natural linewidth would then be 10 kHz, say, corresponding to a kinetic temperature of several hundred degrees (in the absence of turbulence).

Production of a high power gain requires a considerable number of molecules in the line of sight, plus an efficient process for population inversion. If T_b is the brightness temperature in the continuum, and $T(\nu)$ that at the peak of the amplified line, the equation of transfer (neglecting spontaneous emission) gives:

$$\ln \frac{T(\nu)}{T_b} = \frac{c^2}{8\pi\nu^2} \cdot \frac{A_{21}}{\Delta\nu} \cdot \int \left(n_2 - \frac{g_2}{g_1} n_1\right) dl$$
$$= \frac{9{\cdot}1 \times 10^{-10}}{\Delta\nu} \cdot \int \left(n_2 - \frac{g_2}{g_1} n_1\right) dl \qquad (2)$$

at 1665 MHz (Turner 1966). If we take $T(\nu)/T_b = 10^6/10$, and $\Delta\nu = 10$ kHz,

$$\int \left(n_2 - \frac{g_2}{g_1} n_1\right) dl = 1{\cdot}3 \times 10^{14}\ \mathrm{cm}^{-2}. \qquad (3)$$

If the amplifying region has a dimension of 0·1 pc (20″ arc at the distance of W3),

$$\left(n_2 - \frac{g_2}{g_1} n_1\right) \approx 5 \times 10^{-4}\ \mathrm{cm}^{-3}. \qquad (4)$$

If we assume a 1% inversion, which is high for a microwave transition ($T_s = -8$ °K), we thus need $n_2 = 0{\cdot}05$ cm^{-3}.

A density of 0·05 OH molecules per cm³ is very high. If we take $N_H/N_O = 1500/1$ and $N_{OH}/N_O = \alpha$, we need a neutral-hydrogen density $N_H = 75\,\alpha^{-1}$ cm^{-3}. I am relieved

FIG. 9. Photograph of NGC 6334. The OH emission comes from two sources at A and B, both unresolved. (Uppsala Schmidt telescope, Mount Stromlo)

that I may leave it to Salpeter (Paper 8) to give us an estimate of α, and to find a process efficient enough to give a 1% inversion of the OH levels.

If the source size is as small as 0·01 pc, we require a factor 100 more gain in a ten times shorter path, which makes the density estimates 14 times greater.

The degree of inversion must be very different for each of the transitions. If $\ln G_{1665} = 10$ (G being the maser gain), then for the same inversion $\ln G_{1612} = 2$. So $G_{1665}/G_{1612} = 3000/1$, and to explain the observed ratio of 50/1 we must have about three times as much inversion for the 1612-MHz levels. Similarly, to account for the observed 1665/1667 ratio of 4/1 requires that the inversion at 1667 MHz be about half that at 1665 MHz.

II. DETECTION OF INTERSTELLAR $^{18}O^{1}H$

Barrett and Rogers (1964) computed the line frequencies for the isotopic species $^{18}O^{1}H$ from the known frequencies for the most abundant species $^{16}O^{1}H$. For the $F = 2 \rightarrow 2$, $^{2}\Pi_{3/2}$, $\mathcal{J} = 3/2$ Λ-doublet transition they calculated the frequency 1639·3 $\pm$ 0·2 MHz. A search for this line in the spectrum of Sgr A was made at Parkes in July 1965, yielding the results shown in Figure 10 when a linear baseline slope was removed from the measurements. The rest frequency appeared to be 1639·40 MHz from the fit of the measured points to the shape of the $^{16}O^{1}H$ profile (dashed line in Figure 10). The abundance ratio of ^{18}OH to ^{16}OH would be about 1/500, close to the terrestrial $^{18}O/^{16}O$ ratio.

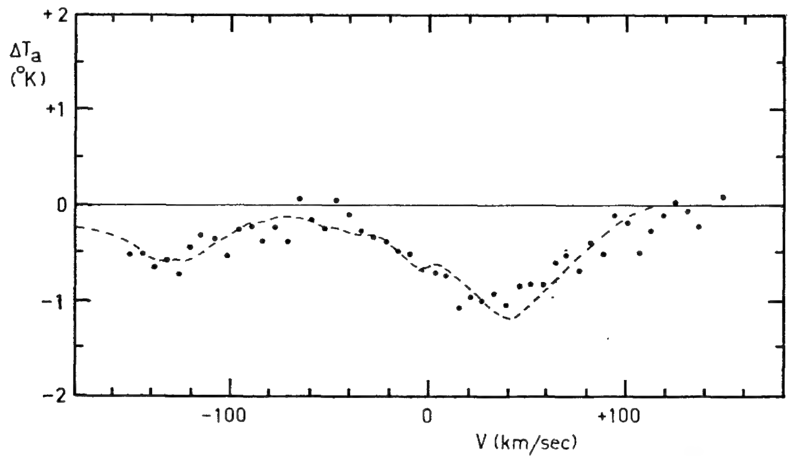

FIG. 10. Absorption of Sagittarius A by OH at 1639·40 MHz, observed with the Parkes 210-foot telescope. The dashed line is the 1667-MHz OH profile scaled and shifted to fit the observed points.

Rogers and Barrett (1966) observed the ^{18}OH absorption of Sgr A early in May 1966 with the NRAO 140-foot telescope. Their results, shown in Figure 11, have a much better signal-to-noise ratio and a wider baseline than the Parkes measurements, and give an $^{18}OH/^{16}OH$ abundance ratio of 1/450 for the absorption feature at +40 km/sec and 1/700 for the feature at -130 km/sec. The rest frequency they determined to be 1639·460 MHz.

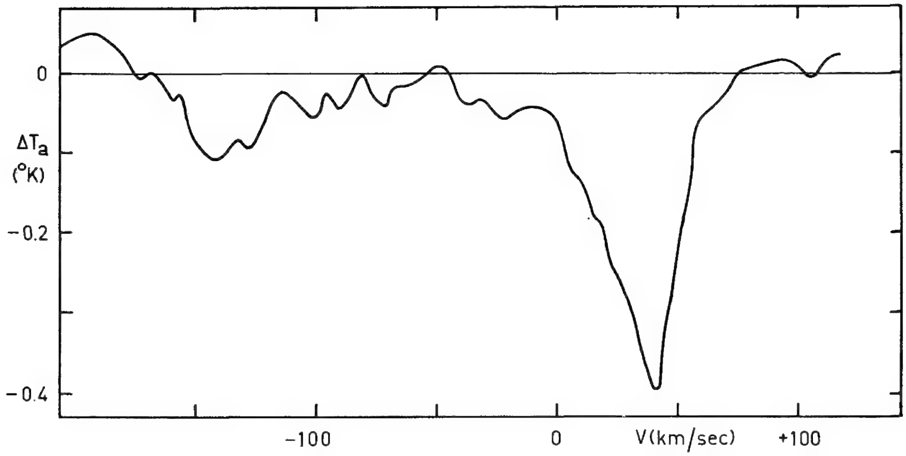

FIG. 11. Absorption of Sagittarius A by OH at 1639·460 MHz, observed with the Green Bank 140-foot telescope. The absorption feature near −130 km/sec is clearly seen.

Later in May 1966, the 1639-MHz line was again detected at Parkes. A brief search for the second strongest $^{18}O^{1}H$ line at 1637·4 MHz was unsuccessful, but indicated that the intensity ratio of these two lines is not appreciably greater than the expected ratio of 5:9. As noted by Herzberg in the discussion (Paper 12), it would be of interest to search for these lines in emission.

12. THE SEARCH FOR MICROWAVE LINES OF OTHER MOLECULES

The strength of the absorption found for $^{16}O^{1}H$ in Sgr A has encouraged several groups to search for lines of other diatomic molecules with an odd number of electrons. The main obstacle here has been that no microwave measurements of the transition frequencies exist, and that computed values, or those determined from optical or infrared spectra, have insufficient accuracy to make a search for a weak line feasible. The detection possibilities for other molecules have been discussed by Barrett (1964) and by Douglas and Elliott (1965).

The molecule with the next highest abundance after OH is CH. The frequency of its Λ-doubling transition in the $^{2}\Pi_{1/2}$ ground state has been determined from infrared and optical spectra as 3400 MHz (Douglas and Elliott 1965), 3350 MHz (Barrett 1966), and 3030 MHz (Goss 1966), each measurement indicating an error of 30 to 60 MHz. There should be three transitions, separated by about 100 MHz, with intensities 1:2:1. A wide band covering the various predicted frequencies has been searched at several observatories. At Parkes the spectrum of Sgr A has been explored from 3120 to 3465 MHz. Any absorption is less than 2%, so that the abundance ratio of CH to OH is less than about 1/50 if the range covered includes one of the transition frequencies. At Hat Creek the range 2850 to 3100 MHz has been searched in Sgr A, Cas A, W 12 and W 51. The MIT group have used the NRAO 140-foot telescope to explore Sgr A (2954 to 3128 MHz and 3330 to 3518 MHz; result: $\tau \leqslant 1\%$) and Cas A (3002 to 3014 MHz, 3072 to 3081 MHz and 3130 to 3470 MHz; with $\tau \leqslant 0{\cdot}3\%$), and have looked for emission from the dark nebula

near AE Aurigae (3340 to 3412 MHz; result: $T_a \leqslant 0.7$ °K). Although these searches have all given negative results, we know that CH is present in the interstellar medium in considerable concentrations, because of its marked absorption at 4300Å (see, for instance, Adams 1949).

A Λ-doublet line of SiH in the $^2\Pi_{1/2}$ ground state has been predicted to occur at 2400 MHz (Townes 1957) or 2940 MHz (Douglas and Elliott 1965). The latter frequency has been covered in the Hat Creek search for CH. The optical depth of six per cent predicted for SiH in the direction of Sgr A (Barrett 1964) would be easily detectable if an accurate frequency were known.

One of the few diatomic hydrides with a measured Λ-doublet transition frequency is SH. In the $^2\Pi_{3/2}, J = 3/2$ state the two strongest transitions are at 111.58 ± 0.10 MHz and 111.26 ± 0.10 MHz, with an intensity ratio of 9:5. The low abundance of sulphur, the low transition probability (proportional to ν^3), and the short lifetime of SH against photodissociation lead one to expect an optical depth of only 10^{-5} for Sgr A. The high level of interference at 111 MHz makes the chances of detection even slimmer. But the accuracy with which the frequency is known is a considerable spur to observational work.

Enormous astrophysical importance would attach to the detection of molecular hydrogen, which is the convenient theoretical repository for the 'missing mass' in the Galaxy and in intergalactic space. There are no ground-state transitions in the microwave spectrum. Hyperfine splitting occurs (Frey and Mizushima 1962) in the metastable $^3\Pi_u$ state of H_2, and other transitions have been suggested for this state (Malville 1964). However, the lifetime of the metastable state is so short that its population should be insignificant under interstellar conditions. The molecular hydrogen ion H_2^+ has a microwave hyperfine spectrum, but the computed frequencies differ considerably (Burke 1960, Dalgarno *et al.* 1960, Mizushima 1960, Stankevič 1960). The ion will rapidly undergo dissociative recombination, and its abundance is probably low.

Because of the anomalous excitation of OH, investigation of other lines in the OH spectrum will demand a considerable amount of radio-astronomical observation. Barrett (1964) has computed the Λ-doublet transitions for the $^2\Pi_{3/2}, J = 5/2$ and $^2\Pi_{1/2}, J = 1/2$ levels of $^{16}O^1H$, which might be populated by the pumping mechanism which inverts the ground state ($^2\Pi_{3/2}, J = 3/2$). Detection of the 54-MHz transitions between the hyperfine levels of the ground state would also be most valuable. But these are magnetic-dipole transitions in a part of the radio spectrum swamped by interference, and pose a difficult detection problem.

REFERENCES

Adams, W. S. 1949, *Astrophys. J.*, **109**, 354.
Barrett, A. H. 1964, *IEEE Trans. Military Electronics*, **8**, 156.
Barrett, A. H. 1966, private communication.
Barrett, A. H., Rogers, A. E. E. 1964, *Nature*, **204**, 62.
Barrett, A. H., Rogers, A. E. E. 1966, *Nature*, **210**, 188.
Bolton, J. G., Van Damme, K. J., Gardner, F. F., Robinson, B. J. 1964*a*, *Nature*, **201**, 279.
Bolton, J. G., Gardner, F. F., McGee, R. X., Robinson, B. J. 1964*b*, *Nature*, **204**, 30.
Burke, B. F. 1960, *Astrophys. J.*, **132**, 514.
Cudaback, D. D., Read, R. B., Rougoor, G. W. 1966, *Phys. Rev. Lett.*, **17**, 452.
Dalgarno, A., Patterson, T. N. L., Somerville, W. B. 1960, *Proc. R. Soc. London Ser. A*, **259**, 100.

Davies, R. D., De Jager, G., Verschuur, G. L. 1966, *Nature*, **209**, 974.
Dieter, N. H., Ewen, H. I. 1964, *Nature*, **201**, 279.
Dieter, N. H., Weaver, H. F., Williams, D. R. W. 1966, *Sky Telesc.*, **31**, 132.
Douglas, A. E., Elliott, G. A. 1965, *Can. J. Phys.*, **43**, 496.
Ehrenstein, G., Townes, C. H., Stevenson, M. J. 1959, *Phys. Rev. Lett.*, **3**, 40.
Frey, D. A., Mizushima, M. 1962, *Phys. Rev.*, **128**, 2683.
Gardner, F. F., Robinson, B. J., Bolton, J. G., Van Damme, K. J. 1964, *Phys. Rev. Lett.*, **13**, 3.
Gardner, F. F., McGee, R. X., Robinson, B. J. 1967, *Austr. J. Phys.* (in press).
Goldstein, S. J., Gundermann, E. J., Penzias, A. A., Lilley, A. E. 1964, *Nature*, **203**, 65.
Goss, W. M. 1966, *Astrophys. J.*, **145**, 707.
Gundermann, E. J. 1965, Thesis, Harvard.
Malville, J. M. 1964, *Astrophys. J.*, **139**, 198.
McGee, R. X., Robinson, B. J., Gardner, F. F., Bolton, J. G. 1965, *Nature*, **208**, 1193.
Mizushima, M. 1960, *Astrophys. J.*, **132**, 493.
Penzias, A. A. 1964, *Astr. J.*, **69**, 146.
Radford, H. E. 1964, *Phys. Rev. Lett.*, **13**, 534.
Robinson, B. J. 1965, *Scient. Am.*, **213**, no. 1, 26.
Robinson, B. J., Gardner, F. F., Van Damme, K. J., Bolton, J. G. 1964, *Nature*, **202**, 989.
Rogers, A. E. E., Barrett, A. H. 1966, *Astr. J.*, **71**, 868.
Rogers, A. E. E., Moran, J. M., Crowther, P. P., Burke, B. F., Meeks, M. L., Ball, J. A., Hyde, G. M. 1966, *Phys. Rev. Lett.*, **17**, 450.
Rogers, A. E. E., Moran, J. M., Crowther, P. P., Burke, B. F., Meeks, M. L., Ball, J. A., Hyde, G. M. 1967. *Astrophys. J.*, **147**, 369.
Stankevič, K. S. 1960, *Astr. Zu.*, **37**, 983; translation in: 1961, *Soviet Astr.*, **4**, 917.
Townes, C. H. 1957, IAU Symposium, no. 4, *Radio Astronomy*, Ed. H. C. van de Hulst, pp. 92–103, Cambridge Univ. Press, Cambridge.
Turner, B. E. 1966, *Nature*, **212**, 184.
Weaver, H. F., Williams, D. R. W. 1964, *Nature*, **201**, 380.
Weaver, H. F., Williams, D. R. W., Dieter, N. H., Lum, W. T. 1965, *Nature*, **208**, 29.
Weinreb, S., Barrett, A. H., Meeks, M. L., Henry, J. C. 1963, *Nature*, **200**, 829.
Weinreb, S., Meeks, M. L., Carter, J. C., Barrett, A. H., Rogers, A. E. E. 1965, *Nature*, **208**, 440.
Zuckerman, B., Lilley, A. E., Penfield, H. 1965, *Nature*, **208**, 441.

NOTE ADDED IN PROOF

Sine the Symposium the OH emission from W 3, W 49, W 75 and Sgr B2 has been observed by the Jodrell Bank-Malvern interferometer (separation $7 \times 10^5 \lambda$). W 3 is found to be a multiple source with components separated by 0·014 pc. The components are unresolved, the upper limit to their size being 5×10^{-4} pc. A lower limit to the brightness temperature for W 3 is 10^{11} °K. The density estimates in Section 10 must then be increased by at least 2×10^3. For $T(\nu)$ exceeding 10^{11} °K the stimulated transition rate is many orders of magnitude greater than the pumping rate for the most efficient inversion process yet proposed. Thus the maser is probably saturated. The number of molecules required to give the observed output must then be greatly increased, while there would be little narrowing of the line-width.

Of 56 galactic continuum sources now observed, 22 show emission—often on the satellite lines only, while the 1665- and 1667-MHz lines display normal absorption. In several cases emission has been located in a different spiral arm from that containing the source. Emission is also associated with two non-thermal sources.

For an account of recent developments see Robinson, B. J., McGee, R. X. 1967, *A. Rev. Astr. Astrophys.*, **5**, in press.

I.A.U. Symposium no. 31, 1967

8. THEORY OF INTERSTELLAR MOLECULES*
(Introductory Report)

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ABSTRACT

Various estimates are described for the rate of formation of hydrogen molecules on the surface of interstellar grains in H I regions. The average abundance of molecular hydrogen relative to atomic hydrogen remains uncertain by a few orders of magnitude.

Possibilities are presented for the formation of OH molecules (and, more briefly, for other diatomic molecules), either on the surface of dust grains or by exchange reactions in the interstellar gas after cloud-cloud collisions. The rate for photodissociation of OH in H I regions is uncertain.

A brief discussion is given of various possible mechanisms for maser action in the OH molecule, such as optical pumping of microwave levels by UV radiation at the edge of an H II region. It appears that the narrow OH emission lines must originate in cool gas bordering an H II region.

1. INTRODUCTION

I shall briefly return later to the exciting questions of OH microwave emission, but mainly deal with the more mundane problems of the formation and destruction of molecules. I shall give very few references, but an extensive bibliography will be found in the excellent review article by Dieter and Goss (1966).

2. FORMATION AND DESTRUCTION OF MOLECULAR HYDROGEN

Let us deal first with molecular hydrogen, which presumably is the most abundant molecule, since hydrogen is by far the most abundant atomic species (ignoring helium which does not form molecules). It is the only molecular species which at least has a chance of being more abundant in interstellar space than all monatomic gases; this could have an important bearing on the question of the 'invisible mass' in our Galaxy as discussed by Oort (1959) and others.

Molecular hydrogen would have one important effect on the interstellar gas, even if present in relatively low abundance. Figure 1 shows *cooling* curves (Gould, Gold and Salpeter 1963) for interstellar gas which has been heated to 3000 °K, say, for different abundance ratios $[H_2]/[H]$ of molecular to atomic hydrogen. A value of this ratio as small as 10^{-4} still increases the cooling rates at the early stages, since molecular hydrogen is a very efficient radiator at temperatures exceeding a few hundred degrees Kelvin. On the other hand, molecular hydrogen is relatively unimportant near or below 100 °K and therefore affects the harmonic-mean temperature of gas clouds rather little.

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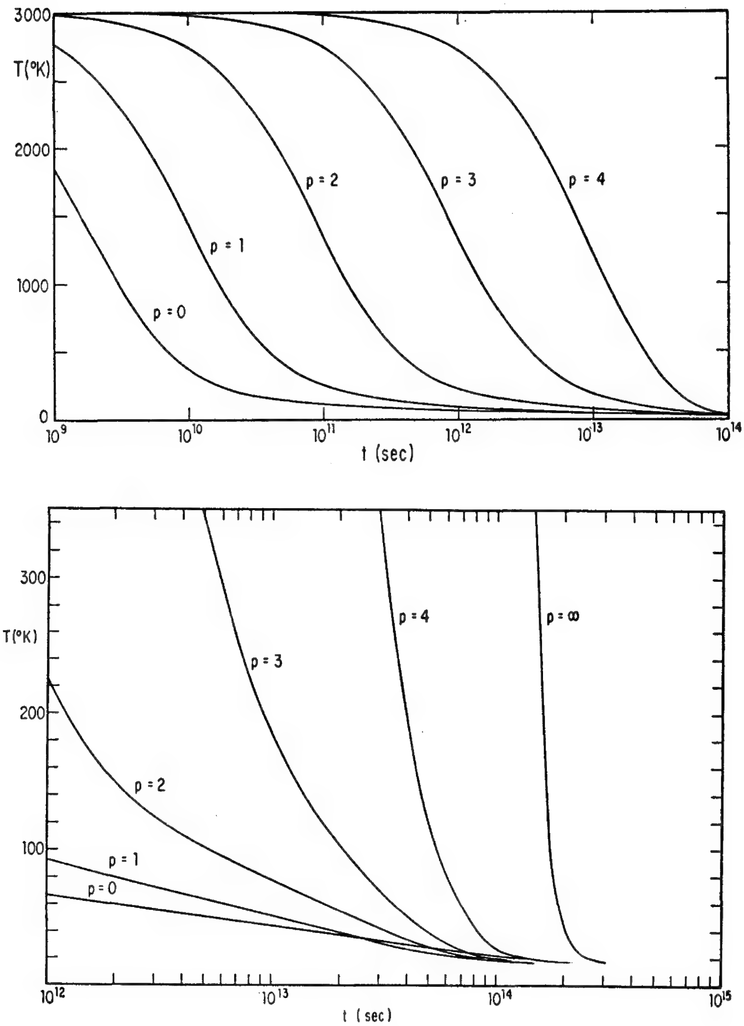

FIG. 1. Temperature T of a cloud (with density 10 H/cm^3) at time t after being heated to 3000 °K. The label p denotes log ([H]/[H_2]). (Gould, Gold and Salpeter 1963)

One question important for estimating abundances of any of the molecules concerns the *threshold photon energy for photodissociation* of the molecule with appreciably large oscillator strengths (allowed transitions). More specifically, the vital question is whether this threshold is higher or lower than 13·6 eV, the Lyman ionization limit of atomic hydrogen. If the threshold is lower, the molecules are dissociated relatively rapidly (in 10^4 or 10^6 years, say), even in neutral-hydrogen gas clouds, by means of the diluted starlight. This is certainly the case for triatomic molecules and such molecules must consequently have a low abundance. For H_2, on the other hand, the threshold for an

allowed dissociating transition is 14·5 eV, and such photons beyond the Lyman edge have a negligibly small abundance in a neutral-hydrogen region. The main cause (Gould and Salpeter 1963) of dissociation for H_2 is the occasional passage of a neutral-gas cloud near enough to an O or B star to ionize the atomic hydrogen. In passing through such a 'Strömgren sphere', which contains a lot of far-ultraviolet photons, the molecular hydrogen is also quickly and completely dissociated. The average rate of passage into such an ionizing region is of the order of once per 10^8 years (Gould *et al.* 1963), and there is little controversy about this dissociation mechanism.

There is also little controversy about the place where hydrogen molecules are formed from hydrogen atoms, namely on the surface of interstellar dust grains. Unfortunately, however, there is great controversy about how large the *surface recombination rate* is. First of all, for a hydrogen atom the rate of hitting the surface of a dust grain depends on the total grain surface area per cm^3. Both the distribution of grain sizes and the overall abundance of grains is somewhat uncertain, but it is very probable (Gould *et al.* 1963, Bates and Spitzer 1951, McCrea and McNally 1960) that the surface hitting rate lies in the range of 10^{-8} to 10^{-6} per year. If the efficiency γ per surface hit for recombination into a gaseous-hydrogen molecule were not much smaller than unity, then the average abundance ratio $[H_2]/[H]$ would be of order unity or somewhat larger. For γ to be close to unity, a hydrogen atom should remain on the grain surface long enough before evaporating to find a partner (Gould and Salpeter 1963, Knaap *et al.* 1966), but the molecules thus formed should eventually evaporate.

If we consider only the *plane surface of a perfect crystal*, atoms are attracted to the grain surface only by the weak Van der Waals forces. Recent calculations (Knaap *et al.* 1966) show that the atoms on such a surface evaporate too rapidly, unless the grain temperature is below about 10 °K, whereas estimates for actual grain temperatures are mostly in the range of 20 to 40 °K. At the *edges of graphite flakes* (Stecher and Williams 1966) hydrogen atoms can be bound with a full chemical bond, more than a hundred times stronger than the Van der Waals attraction. In this case there is no danger of premature evaporation, but an *activation* energy has to be overcome to break the bond and form a hydrogen molecule. Activation energies are usually of the order of four per cent of the bond energy, and a fairly high relative velocity between the hydrogen atoms and the grain is needed in the Stecher-Williams mechanism to give a high efficiency factor γ.

I personally take a more optimistic view: Any *imperfections on the surface of the grain*

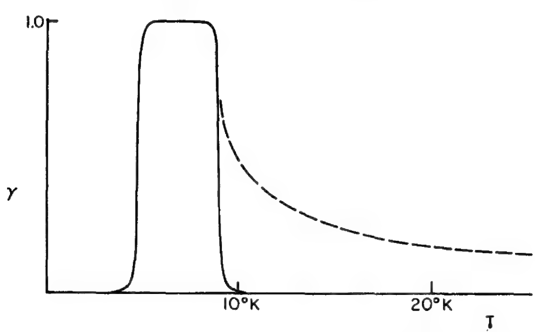

FIG. 2. The efficiency factor γ (as a function of temperature) for a hydrogen atom which has hit a grain surface to recombine and to escape as gaseous molecular hydrogen.

are likely to provide sites with binding energy at least slightly larger than the weak Van der Waals force and at least slightly smaller than a full chemical bond. Over a large range of such binding energies neither premature evaporation nor the activation energy would present any problem. This optimistic view leads to the long tail (dashed) in the efficiency-temperature curve shown schematically in Figure 2 (the solid curve corresponds to the assumption of a perfect crystal surface). Evidently, the situation concerning molecular hydrogen is rather uncertain and I would summarize the predicted abundances as

$$\log\{[H_2]/[H]\} = 0^{+2}_{-3}. \tag{1}$$

3. ABUNDANCE OF OH MOLECULES

Let us turn next to the abundances of other diatomic molecules, more specifically to the hydrides CH, OH, etc. One is tempted to make the same arguments about formation and destruction of such molecules as for H_2, but in fact there are two possible differences.

The first I have mentioned already—if the threshold for photodissociation with appreciable oscillator strength is below 13·6 eV, then dissociation by diluted starlight is quite rapid even in neutral-gas regions. This is definitely known to be the case for CH, and the *average* abundance of this molecule should consequently be rather low. The threshold energy for OH is unfortunately not known as yet, but we conjectured (Carroll and Salpeter 1966) that it may be above 13·6 eV and I will assume this to be the case, just as for H_2.

Although OH can be formed on grains and destroyed near hot stars, just as H_2, we claim a more important mechanism for OH and other minor molecular constituents of interstellar gas: *Two-body gas-kinetic exchange reactions* (Carroll and Salpeter 1966) can convert the more abundant H_2 molecules into hydrides and vice versa. For OH we have

$$H_2 + O + \Delta \rightleftarrows OH + H, \tag{2}$$

with $\Delta = (0{\cdot}10 \pm 0{\cdot}03)$ eV. Besides the reaction energy, Δ, the rates for the reaction in either direction also contain a Boltzmann factor involving an *activation energy* (in the range 0·05 to 0·5 eV). At temperatures of about 100 °K, normal for neutral gas clouds, these rates are much too slow, but every few million years cloud-cloud collisions take place which heat the gas above 1000 °K. Although the gas cools relatively quickly (the quicker the more H_2 it contains), the rates are very fast at the higher temperatures—fast enough for the reactants in the exchange reaction to roughly come to equilibrium. As the gas cools, the rates slow down and the *abundance ratios are 'frozen in'* at some stage. If the H_2 abundance is large, the 'freezing in' occurs at a higher temperature (earlier), which favors OH over O. The resulting abundance ratio [OH]/[O] thus increases more rapidly than linearly as a function of $[H_2]/[H]$. Typical results are:

$[H_2]/[H]$	1	10^{-2}	10^{-3}
[OH]/[O]	0·5	5×10^{-3}	10^{-4}

but these numerical values may easily be in error by factors of three or four. Since the abundance of H_2 as well as the total abundance of oxygen not locked up in grains may vary considerably from place to place, the absolute abundance of OH may well vary very drastically.

4. MICROWAVE EMISSION FROM INTERSTELLAR OH

As Robinson made quite clear in his review (Paper 7), something drastic is going on which must involve *maser pumping* of some kind. First some general remarks. The *narrowness of the observed lines* certainly indicates a maser at work, but the (square of the) factor of narrowing compared to thermal widths increases only logarithmically with the gain. Since gains exceeding 10^{10} or 10^{20} would be quite unreasonable, and line widths corresponding to 10 °K have been observed, the actual temperatures in the region giving the microwave amplification cannot exceed a few hundred degrees. Regions immediately outside of ionized-hydrogen regions are possible, but the *interior of* H II *regions* with typical temperatures of 10^4 °K is *ruled out* (apart from the fact that OH molecules would be rapidly destroyed in such regions). A point which practically all maser mechanisms have in common is a rather *peaked angular distribution*. Because of this 'directional narrowing', the emitting (or amplifying) region can be much larger (at least in one dimension) than the apparent dimensions as inferred, either from an interferometric type of angular-size observation, or from the duration of a 'flash' or other observed time-variation.

There is at the moment no agreement regarding specific *pumping mechanisms* which give the population inversion responsible for maser amplification. There are many rival mechanisms, each with some flaw, none fully worked out and yet each rather promising. There is also no full agreement about the *location* of the activity, but most workers have concentrated on the region just *outside an ionized* H II *region*. This location has the double advantage of relatively low temperature and shielding of the molecules from the *far* UV (beyond the Lyman limit) on the one hand, and some strong activity (high intensity in near ultraviolet, shock waves, fast electrons, etc.) on the other. One class of possible pumping mechanisms would make use of an accidental *resonance* between some emission line coming from the H II region and some upward transition in the OH molecule. Apart from a suggestion by Cook (1966) involving Lyman α, little work on this class has appeared, but Šklovskij mentions some work in progress in the Soviet Union. If a suitable mechanism of this kind can be found, it could have the advantage of high intensity in a narrow spectral region of interest. Another class of mechanisms (Perkins *et al.* 1966, Litvak *et al.* 1966, Field and Turner 1966) makes use of some part of the continuum emission in the UV, or of an electron beam (Johnston 1966) produced in the H II region.

Some of the proposed mechanisms make use of an *anisotropy of the pumping agent*. Just as an example, one such mechanism (Perkins *et al.* 1966) is illustrated in Figure 3. A narrow band of the continuum emission spectrum from the H II region (wavelength in the near UV at about 3008 Å) is absorbed, by means of a strong allowed transition in OH, in a narrow shell immediately outside the ionized region. The bulk of this UV comes from the Balmer continuum in the ionized gas rather than from the hot exciting star (or stars), but hits the OH-shell from the inside only. The excited OH molecules cascade down in a complicated manner, with branching ratios being different for substates with different magnetic quantum numbers. Some substates are pumped by this means into the upper level of the microwave transitions, others into the lower level. The net result is exponential amplification for one component of linear polarization, for a microwave beam travelling at right angles to the main direction of the UV radiation, i.e. travelling tangentially to the surrounding shell.

This particular mechanism in its present form seems to be numerically too weak

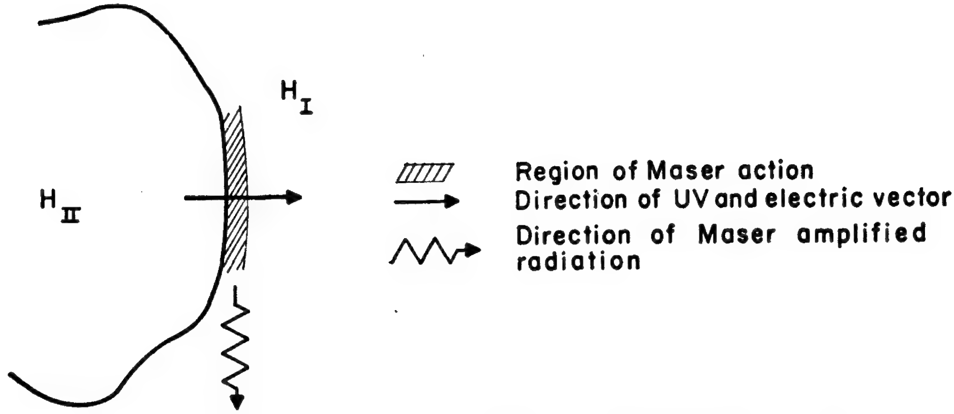

FIG. 3. Geometry of maser action. (Perkins, Gold and Salpeter 1966)

(some infrared photons emitted in the cascade are scattered a number of times, which tends to equalize the populations in the different substates and thus to depress the population inversion); also, it predicts predominantly linear polarization rather than circular. None of the analyses of mechanisms discussed so far are fully satisfactory, nor are they complete. In fact, some of the 'rival calculations' at the moment are not even concerned with different mechanisms but only with different (and radical) approximations applied to the same mechanism. Nevertheless the various attempts to date, crude as they are, are qualitatively close to explaining the spectacular observations, and I feel confident that satisfactory theoretical models will come forth in the not-too-distant future.

REFERENCES

Bates, D. R., Spitzer, L. 1951, *Astrophys. J.*, **113**, 441.
Carroll, T. O., Salpeter, E. E. 1966, *Astrophys. J.*, **143**, 609.
Cook, A. H. 1966, *Nature*, **210**, 611.
Dieter, N. H., Goss, W. M. 1966, *Rev. mod. Phys.*, **38**, 256.
Field, G. B., Turner, B. 1966, in preparation.
Gould, R. J., Salpeter, E. E. 1963, *Astrophys. J.*, **138**, 393.
Gould, R. J., Gold, T., Salpeter, E. E. 1963, *Astrophys. J.*, **138**, 408.
Johnston, I. D. 1966 (July), Report, CSUAC 46, Cornell Univ., Ithaca, N.Y.
Knaap, H. F. P., Van den Meijdenberg, C. J. N., Beenakker, J. J. M., Van de Hulst, H. C. 1966, *Bull. astr. Inst. Netherl.*, **18**, 256, and *Proc. Symp. on Interstellar Grains*, Troy, N.Y. (in press).
Litvak, M. M., McWhorter, A. L., Meeks, M. L., Zeiger, H. J. 1966, *Phys. Rev. Lett.*, **17**, 821.
McCrea, W. H., McNally, D. 1960, *Mon. Not. R. astr. Soc.*, **121**, 238.
Oort, J. H. 1959, *Bull. astr. Inst. Netherl.*, **15**, 45.
Perkins, F., Gold, T., Salpeter, E. E. 1966, *Astrophys. J.*, **145**, 361.
Stecher, T. P., Williams, D. A. 1966, *Astrophys. J.*, **146**, 88.

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9. ANGULAR SIZE OF OH EMISSION REGIONS

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ABSTRACT

Interferometry gives effective diameters less than 20″ for the OH emission sources in W 3 and Sgr B2. The sources in W 49 and NGC 6334 contain two or more components, some of which are smaller than 25″.

The remarkable characteristics of the radiation observed in emission at the OH lambda-doublet frequencies in the vicinity of 18 cm have led us to examine the angular extent of these emission regions. An upper limit of 5′ for the angular size of the region near Sgr B2 (in Lequeux's 1962 notation) has been determined by McGee *et al.* (1965), implying a brightness temperature of at least 1500 °K. In order to achieve greater angular resolution, we have used the Haystack 120-foot (37-m) and Millstone 85-foot (26-m) telescopes of the MIT Lincoln Laboratory as an interferometer, whose baseline is approximately 3800 λ at 18 cm, along a line nearly 20° east of north. For a description of equipment and observational procedure, we refer to Rogers *et al.* (1966).

We observed the OH emission associated with the following continuum sources: W3, W49, NGC6334, and Sgr B2 (W24). The OH sources in W3 and Sgr B2 both seem to be single and of small angular size (less than 20″ effective source diameter, estimated from peak deviations in fringe amplitude). Individual lines at 1665 MHz give positions agreeing to better than 3″ for W3 and to better than 7″ for Sgr B2. Measurements of the 1667-MHz lines in W3 agree in position with the 1665-MHz lines to better than 7″.

The OH emission in W49 comes from two unresolved sources, both with effective diameters less than 25″; individual lines give positions agreeing to better than 7″. The weaker of the two sources is displaced by $+8^{s}.5$ in right ascension and $-68''$ in declination from the position of the principal source.

The OH emission from NGC6334 may be more complex, but is composed of at least two sources, the principal one having an effective diameter of less than 25″. The secondary source or sources could not be accurately located, because of restricted hour-angle coverage and poor signal-to-noise ratio.

The principal-source positions are summarized in Table 1.

Table 1

Principal OH-Source Positions (1950.0)

Source	α	δ
W 3	$02^h\ 23^m\ 16\overset{s}{.}3 \pm 1^s$	$+61°\ 38'\ 57'' \pm 5''$
W 49	$19^h\ 07^m\ 49\overset{s}{.}7 \pm 1^s$	$+9°\ 01'\ 12'' \pm 5''$
Sgr B 2	$17^h\ 44^m\ 11^s \pm 2^s$	$-28°\ 23'\ 29'' \pm 10''$
NGC 6334	$17^h\ 17^m\ 33\overset{s}{.}5 \pm 2^s$	$-35°\ 45'\ 35'' \pm 10''$

Our positions for OH in W3 and W49 agree well with those of Cudaback *et al.* (1966) and our W49 positions allow us to resolve the fringe ambiguities given by them. The position for W3 is nearly the same as that given earlier by us (Rogers *et al.* 1966).

The work was performed at Lincoln Laboratory, which is a center for research operated by the Massachusetts Institute of Technology with the support of the U.S. Air Force. The work was also supported by the National Aeronautics and Space Administration (Grant No. NsG-419) and by the Joint Services Program (Contract No. DA36-039-AMC-03200 (E)).

REFERENCES

Cudaback, D. D., Read, R. B., Rougoor, G. W. 1966, *Phys. Rev. Lett.*, **17**, 452.
Lequeux, J. 1962, *Ann. Astrophys.*, **25**, 221.
McGee, R. X., Robinson, B. J., Gardner, F. F., Bolton, J. G. 1965, *Nature*, **208**, 1193.
Rogers, A. E. E., Moran, J. M., Crowther, P. P., Burke, B. F., Meeks, M. L., Ball, J. A., Hyde, G. M. 1966, *Phys. Rev. Lett.*, **17**, 450.

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10. BERKELEY RESULTS ON OH EMISSION

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ABSTRACT

This paper briefly summarizes studies of the position, polarization, and spectral variations of OH emission sources.

Since our first report on emission from the OH molecule (Weaver *et al.* 1965) we have extended the observations to the H II regions W49, IC1795, NGC6334, Orion A, W75 (in Cygnus X), W51, and Sgr B2—all observed with a bandwidth of 2 kHz (0·36 km/sec). At the four line frequencies we have found in the profiles a total of 80 separate features with an average width of 6·4 kHz (1·2 km/sec). The velocities of these features are separated by an average of 0·1 km/sec (omitting two features in Orion A with velocities of +26 and +28 km/sec) from those of the associated H II regions, as determined from our observations of the hydrogen recombination line 157 α at 1683 MHz (Dieter 1967). The intensity ratio of the lines in the OH multiplet is anomalous in all these sources in as extreme a way as found in our original observations (Weaver *et al.* 1965, Dieter *et al.* 1966). No explanation based on equilibrium conditions can possibly explain these line ratios.

In three additional H II regions (W33, W42, W43) Goss (1967) has found OH emission, observed as yet only with the relatively low resolution of 10 kHz (1·8 km/sec). One of these, W43, is particularly interesting in that one of its spectral components differs in velocity by 50 km/sec from that of the H II region in the same direction. This may be the first case of OH emission observed in the absence of a detectable H II region nearby.

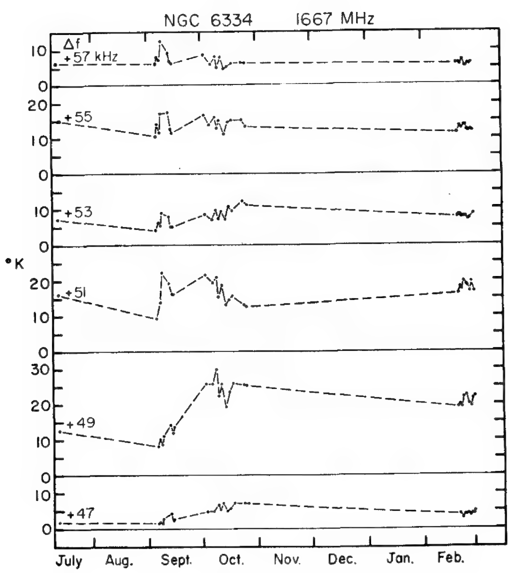
In the more thoroughly observed sources we have found positions for individual line components by observing a grid of positions around the location of the emission. The standard error of the mean of a Gaussian fit to these observations is approximately $\pm 0\!'\!.5$. For two sources, IC1795 and W49, we can compare our positions with those determined by interferometry at Cal Tech and MIT (Cudaback *et al.* 1966, Rogers *et al.* 1966); they agree within the errors of each determination. In both these sources the OH emission comes from the edge of the H II region. NGC6334 is, as usual, an interesting case, with the emission at 1665 MHz coming from two different centers separated by about 10 minutes of arc, and that at 1667 MHz coming from one of the 1665-MHz centers. Both lie in obscured regions away from the center of the H II region (although this source is very complex in appearance, and it is difficult to locate the optical center). Orion A is, as usual, an exception: the OH emission comes, within the limits of error of our measurements, from the direction of the center of the H II region.

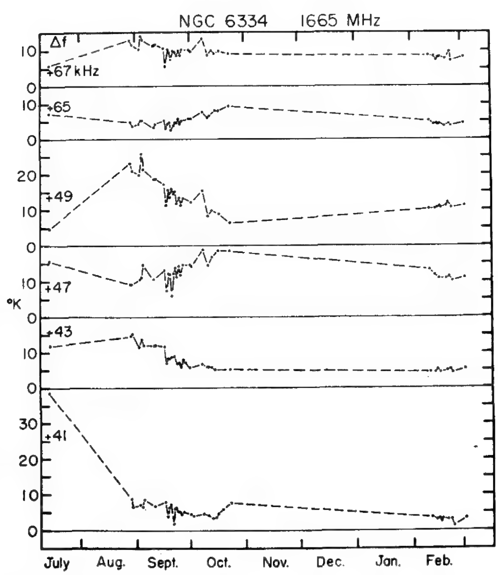
We have found linear polarization, following the discovery of this effect by Weinreb *et al.* (1965) at MIT, in some components of the emission from IC1795, W51, W75, and NGC6334. In individual line components the percentage and position angle of the

polarization seem to be independent of those in adjacent components (Dieter *et al.* 1966). In NGC6334, for example, one line component at 1665 MHz has $35 \pm 5\%$ linear polarization at a position angle of $160° \pm 10°$, and a nearby one has $85 \pm 5\%$ at $73° \pm 3°$.

All but two of the sources observed by us have remained constant in intensity during the observing period, July 1965 to March 1966. The two exceptions (Dieter *et al.* 1966) are NGC6334 and Orion A. The latter shows a change in one part of the profile of about a factor of 1·5, but the low intensity of the source (about 3 °K antenna temperature) makes this difficult to establish beyond doubt. NGC6334 is, however, very different. In this source, some components of the lines at 1667 and 1665 MHz vary strongly in intensity with time, while others remain constant. At 1667 MHz (Figure 1), for example, the component at +49 kHz = −8·8 km/sec (with respect to the local standard of rest) decreased from T_a = 12 °K in July 1965 to 9 °K in September, increased to 25 °K by mid-October and decreased to 20 °K by mid-February 1966. At 1665 MHz (Figure 2), the component with the same velocity increased from 5 to 23 °K from July to September, decreased steadily to 6 °K by mid-October and increased to 11 °K by February. The absence of correlation between the two frequencies is typical, but not invariable. The components within a given profile certainly do vary independently.

One proposed explanation of the variations at 1665 MHz is that apparent variations may result from poor antenna pointing. The error would have to be about 7 minutes of arc to produce the sort of changes we have seen, and the three line components would have to vary in unison. No such pointing error is apparent in other sources, and the grids observed about this source itself provide evidence against this interpretation. If





FIGS. 1 and 2. Intensity variations between July 1965 and February 1966 in the 1667- and 1665-MHz emission observed from NGC 6334. Measurements in individual channels (each 2 kHz = 0·4 km/sec wide) are shown; frequency shifts Δf are given with respect to the local standard of rest. Intensities are in °K of antenna temperature.

one attributes all deviations of the observed intensities from a Gaussian fit to errors in antenna pointing and none to uncertainties in intensity, one can obtain an estimate of the error in position at each point of the grid observed. In a typical case the maximum error of the eleven points observed is $2'.5$ and the average is $0'.0$. In addition, one of the components has remained essentially constant while the other two (which are 4 kHz apart) have varied out of phase with one another. Perhaps an explanation should be sought in the instability of the mechanism producing the radiation.

We are convinced that one must be extremely cautious in making general statements about emission from the OH molecule. One must investigate carefully the minute details of the profiles and discuss them on an individual basis.

REFERENCES

Cudaback, D. D., Read, R. B., Rougoor, G. W. 1966, *Phys. Rev. Lett.*, **17**, 452.
Dieter, N. H. 1967, in preparation.
Dieter, N. H., Weaver, H. F., Williams, D. R. W. 1966, *Sky Telesc.*, **31**, 132.
Goss, W. M. 1967, *Astr. J.*, **72**, 300.
Rogers, A. E. E., Moran, J. M., Crowther, P. P., Burke, B. F., Meeks, M. L., Ball, J. A., Hyde, G. M. 1966, *Phys. Rev. Lett.*, **17**, 450.
Weaver, H. F., Williams, D. R. W., Dieter, N. H., Lum, W. T. 1965, *Nature*, **208**, 29.
Weinreb, S., Meeks, M. L., Carter, J. C., Barrett, A. H., Rogers, A. E. E. 1965, *Nature*, **208**, 440.

11. ANOMALOUS OH ABSORPTION IN THE DIRECTION OF CASSIOPEIA A*

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ABSTRACT

At radial velocities around zero, the optical depths in the 1665- and 1667-MHz OH absorption lines in the spectrum of Cas A are in the expected ratio, 5 : 9. In both lines, the zero-velocity component is split into two clearly-resolved features. However, neither the 1612- nor the 1720-MHz lines shows any splitting. Absorption in the 1612-MHz line is stronger than expected, while the 1720-MHz line shows evidence of emission.

The analysis of complex OH-emission spectra at the four ground-state frequencies in terms of Zeeman patterns requires an accurate knowledge of the *rest frequencies* of the four lines. The most accurate values available are those of Radford (1964) shown in Table 1. These values, whose accuracy of ± 2 kHz is defined as four times the standard deviation of the measurements, appear mutually inconsistent. The line rest frequencies must obey the sum rule

$$\nu_{1612} + \nu_{1720} = \nu_{1665} + \nu_{1667}, \qquad (1)$$

but the values of Table 1 fail by 5 kHz. A discrepancy of this amount is equivalent to approximately 1 km/s in radial velocity, so that in complex spectra attempts to match the components of any two OH lines become subject to some uncertainty.

Table 1

Laboratory determination of the OH rest frequencies (Radford 1964)

Transition	Frequency (kHz)
$F = 1 \rightarrow 2$	1 612 231 ± 2
$F = 1 \rightarrow 1$	1 665 401 ± 2
$F = 2 \rightarrow 2$	1 667 358 ± 2
$F = 2 \rightarrow 1$	1 720 533 ± 2

Partially to overcome these difficulties, we have taken a series of absorption observations with high frequency resolution in the direction of Cassiopeia A. Previous observations of this source showed excellent agreement between laboratory and astronomical determinations of the OH rest frequencies, on the assumption that interstellar OH had the same radial velocity as hydrogen; but observations had only been made at 1665 and 1667 MHz (Radford 1964). In addition, Barrett *et al.* (1964) found the OH absorption line at radial velocity $-0{\cdot}8$ km/sec in the spectrum of Cas A to be split into two components

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of 4 to 5 kHz width; thus, the Cas A absorption lines at −0·8 km/sec appeared well-suited for an accurate determination of the rest frequencies. The observations reported here were made with the 140-foot (43-m) telescope of the National Radio Astronomy Observatory at Green Bank, West Virginia. The receiver was similar to that used in our polarization studies (Barrett and Rogers 1966).

As shown in Figure 1, the −0·8 km/sec absorption line in Cas A is well resolved into two components at both 1665 and 1667 MHz. Within the noise limitations of the observations, the line intensities are in the ratio 5:9, in agreement with previous observations (Weinreb *et al.* 1963). However, neither the 1612- nor the 1720-MHz line shows the splitting. Not only was this result quite unexpected, but it prevents a determination of the rest frequencies of the lines until it is understood.

The 1720-MHz observations shown in Figure 1 may give evidence of OH *emission* at a velocity of about +1 km/sec, although the noise level of the measurements is such that further observations are required to confirm this. It is also clear that the absorption at 1612 MHz is greater than that which would be predicted if the 1612:1665:1667:1720 intensity ratios were 1:5:9:1. Since the observed optical depths are less than 0·02, departures from the theoretical line intensities cannot be attributed to optical-depth effects. One might argue that large optical depths are permitted if the OH clouds have

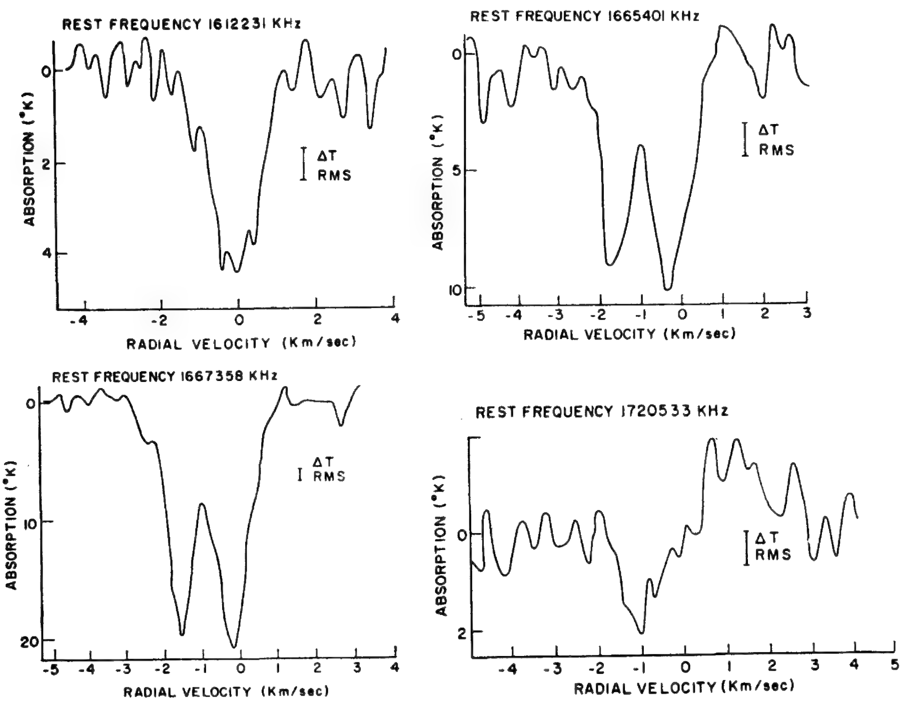

FIG. 1. OH absorption spectra in the direction of Cassiopeia A. The bandwidth used is 1 kHz = 0·2 km/sec; integration times are 4^h, 1^h, 2^h, and 4^h, respectively (in order of increasing line frequency). As noted in the text, the velocity scales may require slight adjustments because of the uncertainty in the rest frequencies.

angular sizes much smaller than the radio source, but the agreement of the observed absorptions at 1665 and 1667 MHz with the theoretical ratio of 5:9 would seem to rule this out.

The presence of strong absorption at 1612 MHz and of reduced absorption, or of emission, at 1720 MHz can be understood theoretically by a consideration of energy-level populations. If the intensity of each transition ν_{ij} corresponds to its own excitation temperature T_{ij}, defined in the usual manner:

$$\frac{N_i}{N_j} = \frac{g_i}{g_j} \exp\left\{-\frac{h\,\nu_{ij}}{k\,T_{ij}}\right\} , \tag{2}$$

and if $kT_{ij} > h\,\nu_{ij}$, it is quite simple to show that the values of T_{ij} must obey the equation

$$\frac{1}{T_{1612}} + \frac{1}{T_{1720}} = \frac{1}{T_{1665}} + \frac{1}{T_{1667}} . \tag{3}$$

For small optical depths this equation can be written in terms of the observed absorption profiles, $\Delta T(\nu)_{ij}$,

$$\Delta T(\nu)_{1612} + \Delta T(\nu)_{1720} = \frac{\Delta T(\nu)_{1665}}{5} + \frac{\Delta T(\nu)_{1667}}{9} , \tag{4}$$

where the denominators 1, 5, and 9 represent the ratios of the optical depths and are a direct result of the statistical weights and transition probabilities of the four lines. Accurate rest frequencies would allow equation (4) to be written as a function of radial velocity. Because the rest frequencies are not accurately known, the velocity scales of Figure 1 are subject to some adjustment. The observations can be used to test the validity of equation (4), however, by integration over the line profiles. Within the noise limitations of the observations, the equation is found to be satisfied.

Equation (4) demonstrates that strong absorption at 1612 MHz must be offset by reduced absorption, or by emission, at 1720 MHz if the 1665- and 1667-MHz absorptions are in the ratio 5:9. Note that equation (3) is a general result, which must be satisfied by whatever mechanism is responsible for establishing the various energy-level populations. Since the excitation temperatures T_{ij} may assume positive as well as negative values, population-inverting mechanisms (masering) must also conform to equation (3). The assignment of individual excitation temperatures to the transitions, which leads automatically to equation (3), is simply another way of stating that the population mechanism must give different populations for the different energy levels, i.e. the mechanism must be dependent on the total quantum number, F.

REFERENCES

Barrett, A. H., Meeks, M. L., Weinreb, S. 1964, *Nature*, **202**, 475.
Barrett, A. H., Rogers, A. E. E. 1966, *Nature*, **210**, 188.
Radford, H. E. 1964, *Phys. Rev. Lett.*, **13**, 534.
Weinreb, S., Barrett, A. H., Meeks, M. L., Henry, J. C. 1963, *Nature*, **200**, 829.

NOTE ADDED IN PROOF

The presence of emission at 1720 MHz, and the lack of line splitting at 1612 and 1720 MHz, have been independently confirmed after the Symposium by Goss (1967).

Goss, W. M. 1967, *Astr. J.*, **72**, 300.

I.A.U. Symposium no. 31, 1967

12. DISCUSSION ON INTERSTELLAR MOLECULES

Miss A. B. Underhill asks Mrs Dieter: How secure is the high point for July 1965 in the lowest section of your 1665-MHz diagram (Paper 10, Figure 2)? If this were only one observation and it were disregarded, the apparent decrease would not be substantial.

Mrs N. H. Dieter answers: The point is more secure than is apparent. On this date several observations around the central position were made, and they confirm the shape of the profile. In addition, at several other frequencies the variations are substantial – up to factors of five in intensity.

G. H. Herbig asks: Is the optical thickness of the OH in the Earth's atmosphere completely negligible?

Mrs Dieter answers: Yes. It has never been detected.

D. S. Heeschen asks: Do intensity variations show in the integrated line profiles?

Mrs Dieter answers: Yes. In NGC6334, at 1665 MHz the integrated intensity has decreased by about 30% while it has increased at 1667 MHz.

H. van Woerden remarks: The OH emission observed by Rogers and Barrett (Paper 11, Figure 1) in the 1720-MHz line at the position of Cas A is only twice the r.m.s. error of antenna temperature. If its velocity width is only a few times the receiver bandwidth, the question appears justified whether this emission has been confirmed by others.

A. H. Barrett answers: To the best of our knowledge, the observations reported have not been confirmed by others. It has generally been assumed, erroneously and without justification, that the OH absorption spectrum of Cas A was 'normal' and, therefore, uninteresting in view of the problems presented by the OH emission in other sources. Thus, observations of the satellite lines at 1612 and 1720 MHz in the absorption spectrum of Cas A have been lacking.

G. L. Verschuur asks Barrett: In view of the weak emission seen at 1720 MHz, is it likely that you would have seen a correspondingly weak feature on your 1665 MHz spectrum, next to the relatively strong 'normal' absorption line?

Barrett answers: Weak emission adjacent to, or blended with, the absorption at 1665 MHz (or 1667 MHz) could have escaped detection in the preliminary observations presented here. However, the observed absorptions at 1665 and 1667 MHz are (within the limit of the observational uncertainties) in the ratio 5:9 over the full profiles, in good agreement with theoretical expectations for small optical depths. This fact might be taken as an argument for the absence of emission at 1665 and 1667 MHz, or for emission at both frequencies in the ratio 5:9, blended with the absorption. Improved observations are required to clarify the situation.

Van Woerden: Is anybody else looking at this emission?

H. F. Weaver: Everyone else has his hands full with his own program.

Weaver further comments: (*a*) There has been frequent reference to the theoretical ratio of 9:5:1:1 for the four OH lines. It should be clearly stated that this is the intensity ratio for vanishingly small optical depth. As a function of optical depth, these lines may have intensity ratios between 9:5:1:1 and 1:1:1:1, the latter ratio being attained for infinite optical depth. To specify the line intensity ratio as a function of optical depth, one must, of course, take into account the appropriate curve of growth.

(*b*) In the direction towards the galactic center, and probably connected with the structure from which the line at −133 km/sec arises, an OH emission line is observed. This appears to be a second case of OH emission having no connection with an H II region.

R. D. Davies: The circular and linear polarizations observed in the OH emission sources require explanation. In our report on the first observation of circular polarization (Davies, R. D., De Jager, G., Verschuur, G. L. 1966, *Nature*, **209**, 974) we interpreted our data in terms of a simple Zeeman pattern. It is now clear that maser action is operative; we should not expect to see the simple Zeeman-splitting pattern, because on maser amplification the relative intensities of the components would not be preserved. However, the Zeeman-splitting process should be kept in mind as a possible means of providing the observed polarization properties. The observation of 100% circular polarization would seem to suggest the presence of fields, strong enough to split the lines completely into left- and right-hand polarized components. The required fields of about 10^{-3} gauss are not improbable in the very compact regions responsible for the OH emission.

T. K. Menon: Recently I have made observations of the OH absorption lines against 40 sources, of which 15 showed definite absorption lines. The second largest optical depth was observed for the source IC434, near ζ Orionis: $\tau = 0{\cdot}11$; for Sgr A $\tau \approx 1$; in most other sources τ was of the order of 0·01.

S. J. Goldstein: In her 1965 Harvard thesis, Ellen J. Gundermann has treated the problem of explaining the observed intensities at 1612, 1665, and 1667 MHz. She found that optical-depth effects could account for the observed intensity ratios in 12 out of 14 features in the galactic plane near the centre.

M. P. Savedoff: Interpretation of angular sizes (Paper 9) is difficult, as for a coherent radiation source the contributions from different parts of the source must be added coherently. Thus, the angular size may be much larger than inferred from the interpretation of interferometric records.

G. W. Rougoor answers: In the case of phase-coherent radiation, the true diameter of OH sources cannot be determined with any observing method.

B. F. Burke: No one has asked Rougoor or me if our accurate positions (cf. Paper 7, Section 8) have yielded optical identification. The answer is no.

M. S. Roberts: We have searched for OH in half a dozen galaxies. No signal was found, to an antenna-temperature limit of 0·1 °K. For a uniform distribution of OH, this sets an upper limit of about 10^{-6} on the abundance ratio of OH to neutral hydrogen.

G. Herzberg: I should like to ask whether ^{18}OH has been observed in emission. If the emission by ^{16}OH is due to maser action, it is likely that ^{18}OH would not appear in emission. Conversely, if the absence of emission by ^{18}OH could be established, this would lend support to the maser mechanism of the ^{16}OH emission.

B. J. Robinson answers: So far, ^{18}OH has only been observed in absorption, as discussed in Section 11 of Paper 7. However the first OH observer home should look for emission at 1637·4 MHz in W3 or W49. Such measurements would give a good indication whether the excitation process for ^{16}OH is highly selective or not.

G. Westerhout: Can we not delegate somebody to go home now and telephone back his results tomorrow afternoon?

H. van Woerden: In the radio spectrum, OH has been observed and CH has not. Salpeter (Paper 8, Section 3) indicates that this agrees with the expected relative abundances of OH and CH as affected by the radiation field. In the optical spectrum, CH has been observed but attempts to detect OH near 3078 Å have failed (Goss, W. M., Spinrad, H., 1966, *Astrophys. J.*, **143**, 989; Gaustad, J. E., Van Woerden, H., in preparation). Can Herbig comment whether this situation is consistent with the expected abundances?

G. H. Herbig answers: I do not recall the ratio of *f*-values, but the equivalent widths of the interstellar lines of CH and CH^+ in ζ Ophiuchi are an order of magnitude greater than the upper limit on the strengths of the OH lines. I regard as very significant the fact that interstellar NH has not been found, despite intensive search, favourable spectral region, and good *f*-value. This seems to me to be a distinct difficulty for the theory of molecular formation on grains, where NH should be produced in comparable quantity to CH.

J. M. Greenberg: Is the shape of a graphite grain critical in determining whether formation of H_2 molecules on their surface takes place? Must the grains be flakes to exhibit sufficient points of high formation probability? I ask this question because, according to Wickramasinghe and Donn, to match the wavelength-dependence of polarization by graphite it is required that only large graphite flakes give the polarization, while the small graphite particles (which dominate the extinction) should be more or less spherical. This would mean, if spherical particles are relatively inefficient in producing H_2, that only a small fraction of the total surface area of interstellar grains is available for this process.

Further it is perhaps worth pointing out that the total surface area of interstellar grains producing a given extinction is only slightly dependent on the kind of grain—whether graphite or metallic. This is because the extinction efficiency of the grain is (in the visible) of the order of unity, irrespective of whether dielectric or metallic grains are considered.

E. E. Salpeter answers: The Donn-Stecher mechanism in its purest form discusses full valence bonds, which are possible at crystal edges in flakes but would not be possible in spherical grains. In my more optimistic view only surface irregularities are required, which may also occur on 'more or less spherical' grains.

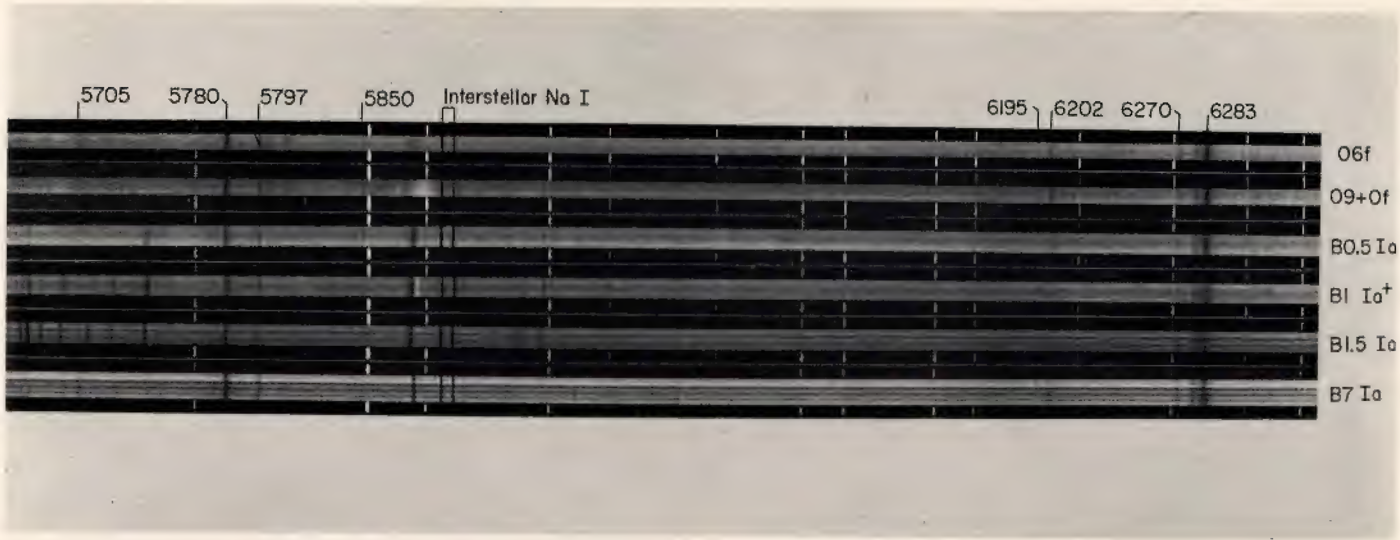

FIG. 1. Spectrograms of the region 5700 to 6300 Å in six reddened early-type stars (from top to bottom: BD + 40° 4227, + 40° 4220, HD 194 839, 169 454, 194 279, 183 143). Eight diffuse interstellar absorption features, and the sharp interstellar lines of Na at 5890 and 5896 Å, are marked along the top edge. The spectrograms were taken with the coudé spectrograph of the Lick 120-inch reflector; the original dispersion was 16 Å/mm.

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13. THE DIFFUSE INTERSTELLAR BANDS III: THE SITUATION IN 1966*

(Invited Paper)

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ABSTRACT

Several possible identifications for the diffuse interstellar lines are reviewed. The strong correlation of diffuse-line strength and of interstellar extinction in the continuum, as well as the break in the extinction curve close to the wavelength of the strongest diffuse line (4430 Å), indicates that the absorber is closely associated with the solid particles. Possibly a molecule frozen on or in the grains may be responsible. Other possibilities considered include a negative ion with 2.8 eV as ionization limit, and free polyatomic molecules.

The diffuse lines were clearly recognized to be of interstellar origin some 30 years ago. They still remain unidentified despite a steadily increasing body of information on their wavelengths, profiles, systematics, etc. This is surely one of the most challenging spectroscopic puzzles since the days of 'coronium' and 'nebulium', and possibly its solution might be of equal significance.

To summarize what is now known about these features, there are now recognized *26 diffuse lines*, or bands, that are certainly of interstellar origin, plus several more that are in the category of 'probable'. A few are quite sharp (Figure 1) ; only at high dispersion can it be seen that these are not quite so narrow as the ordinary interstellar atomic lines in the same spectra. At the other extreme are several very broad, shallow bands, over 50 Å wide at half peak intensity, that are visible only on microphotometer tracings, or even on computer-averaged tracings of a number of spectrograms. This complex absorption spectrum appears to *increase linearly in strength with the optical thickness of the interstellar dust*, but the correlation is not perfect: in some stars the diffuse lines are genuinely too strong, or in other cases too weak, for the amount of interstellar reddening and a mean regression line. There is some reason to suspect that the correlation may be somewhat better with the total extinction than with the reddening, but this is not proven. Furthermore, in a few stars one or two of the diffuse lines appear anomalously weak with respect to all the others. But with these exceptions the complete diffuse-line spectrum seems to change in strength as a whole, maintaining line-intensity ratios to within the accuracy of the observations.

The *amount of energy removed* by the diffuse-line spectrum is not negligible. For example, in the heavily-reddened B7 Ia supergiant HD 183 143, for which $A_v = 4{\cdot}0$

Contributions from the Lick Observatory, No. 224. The earlier papers in this series (Herbig 1963, 1966) were concerned with a possible identification of the λ4430 band, and with its profile in HD 183 143.

magnitudes, τ (5500 Å) = 3·7, the losses with respect to the reddened continuous spectrum are (Herbig, unpublished):

Total equivalent width (*EW*) of the molecular interstellar lines of CH and CH^+, 3957 to 4300 Å:		0·25 Å
Total *EW* of atomic interstellar lines:	Na (D_1, D_2)	1·53
	Ca^+ (H, K)	1·72
	Ti^+ (λ 3383)	0·12
Total *EW* of diffuse lines (4400 to 6700 Å):		20·6 Å

It must be remembered however that these equivalent widths are not directly indicative of relative abundances, because the stronger atomic lines are saturated while the diffuse lines are not.

Since the lower state for the diffuse lines must under interstellar conditions be the ground state of the absorber, we can in effect construct an *energy-level diagram* directly. The survey for diffuse lines is now quite complete from 6800 to about 3300 Å (1·8 to 3·7 eV), and somewhat less complete to 8800 Å (1.4 eV). It is striking that all the known diffuse lines fall in the narrow energy range 1·9 to 2·8 eV. Furthermore, only sharp lines occur at the low-energy end of this range (Figure 2). There may be here the hint that the cutoff near 2·8 eV represents an *ionization or dissociation limit*. If this cutoff is due to the removal of an electron, then the low value suggests a negative ion as the absorber, as was proposed long ago by Herzberg (1955). But either process destroys the carrier, and we must be sure that it is possible for this atom or molecule to be replaced quickly enough to maintain the population, a difficulty pointed out by R. Wilson (1964). The mean time between absorptions of a quantum of the galactic radiation field by an absorber having a resonance transition of oscillator strength f near 4500 Å is only about $0{\cdot}4/f$ years. With such a short lifetime, it is clear that we must replace this ionized or dissociated

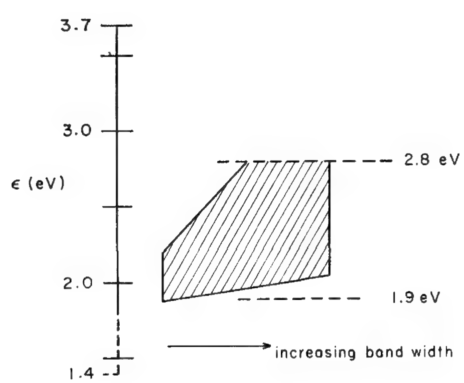

FIG. 2. Schematic energy-level diagram of the diffuse interstellar bands. The ordinate is energy of the level above the ground state, and the abscissa is band width. The shaded region contains the observed levels. Although the spectral region covered extends upward to 3·7 eV and downward to 1·4 eV (with lower completeness between 1·4 and 1·8 eV), no diffuse bands have been found with certainty outside the interval 1·9 to 2·8 eV. Note that the sharper lines occur preferentially at lower energies, on the average.

absorber under the physical circumstances *now* available along the line of sight to a given star. In the case of HD 183 143, there is no associated H II region and no luminous evidence of any cloud collision in that line of sight; yet such special conditions seem to be required by current speculations (Stecher and Williams 1966) on molecule formation on grain surfaces in the interstellar medium. This is a very serious difficulty for the idea that the diffuse bands are due to a process which destroys the carrier. A further problem with the hypothesis that the diffuse bands are due to ions (of either charge) is the observed fact that the bands seem to appear in both H I and H II regions.

There is quite another way of regarding this phenomenon. It has been recognized through the work of Nandy (1964), of Underhill and Walker (1966), and others that the wavelength dependence of the optical thickness of the interstellar dust can in our part of the spectrum be represented quite well by two straight lines which meet near 2·8 eV

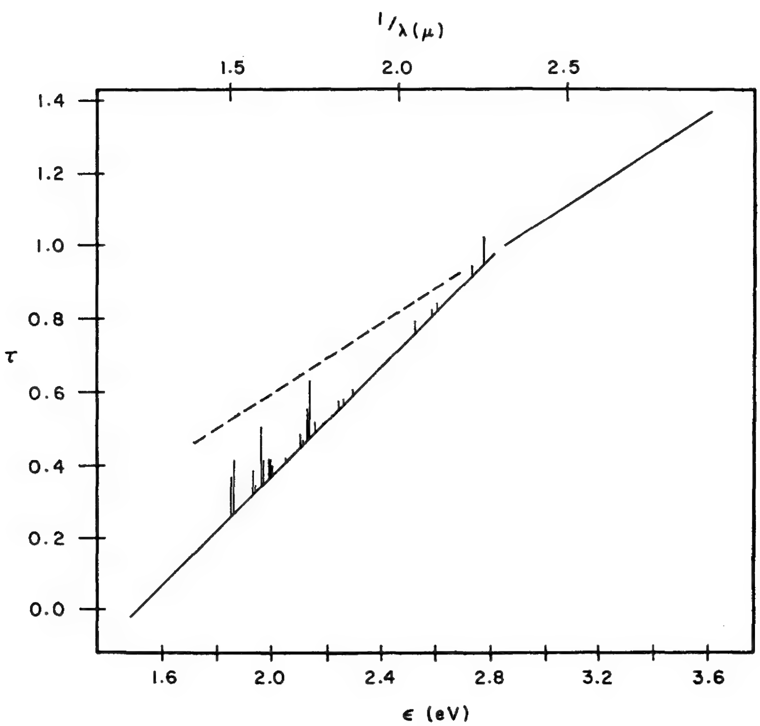

FIG. 3. The 'mean reddening curve' for Cygnus, from Nandy (1964), is shown as two straight lines. The ordinate is optical thickness, the abscissa is energy (below) or frequency (above). The τ-scale has an arbitrary zero point. The central depths in τ-units of the diffuse interstellar lines observed in HD 183 143, reduced by a factor of 2·8 to Nandy's scale, are plotted as vertical lines extending upward from the reddening curve; λ4430 is the line near $1/\lambda = 2{\cdot}25$. Note that all the diffuse bands lie toward lower energies from the point, near 2·8 eV, where the change in slope of the reddening curve occurs. Furthermore, with the exception of λ4430, all lie below the dashed line, which is the extension of the reddening line determined at $\epsilon > 2{\cdot}8$ eV toward lower energies.

(Figure 3). It is interesting that all the diffuse lines now known are found on the low-energy side of this break at 2·8 eV, with the strongest one of all (λ4430) lying very near the break itself (Walker 1966, Herbig 1966). These could be only coincidences. But if not, they indicate that the carrier of the diffuse lines must be physically associated in some way with the solid scattering particles.

This leads back to the old idea that the diffuse lines are due to some familiar *atom or molecule frozen on or in the solid particles*, with its spectrum rendered unrecognizable by the level shifts, selection rule changes, and other perturbations induced by the electric fields of the solid. There are some well-known difficulties with this suggestion, but personally I prefer it because of my feeling that, if the diffuse-line spectrum were due to conventional absorption by one or two *free* atoms or diatomic molecules, there are now enough lines known with accurate wavelengths that some convincing series of spacing regularities ought to have been found. They have not, despite rather intensive search. Herzberg (1955, 1965) reminds us that there are still many unexplored possibilities among the electronic spectra of free polyatomic molecules that could defy elementary analysis. In answer to this, I can only point to Figure 3 and ask: why should the spectrum of a *free* molecule exhibit any such relationship with the optical properties of the solid particles? Furthermore, the strength of the diffuse lines does not correlate well with the strength of the interstellar lines of diatomic molecules (CN, CH^+ and, with lesser certainty, CH) in those stars in which the molecular lines are unusually strong. It is not obvious why a polyatomic molecule would be expected to behave differently from the diatomics.

The optical properties of small solid particles differ greatly from those of stellar atmospheres, but if this were a stellar absorption spectrum, the explanation of Figure 3 would be obvious. On the low-opacity side of a break in the continuous absorption coefficient (as at the Balmer limit), one can see deeper into the star and the absorption lines become correspondingly stronger. If the analogy were applicable to the interstellar case, the diffuse lines could be due to true absorption within particles which become increasingly transparent to wavelengths longer than about 4430 Å. To avoid the difficulties with absorption bands in scattering particles that were pointed out by Van de Hulst (1949), we require that these host particles for the absorbers be very small ($r \sim 300$ Å), in which case they will not contribute very much to the total interstellar-scattering opacity. This idea requires that the depth of the diffuse lines never become greater than the value corresponding to complete opacity of the particle at that wavelength. That is, when plotted in Figure 3, the total opacity due to particle extinction plus diffuse-line absorption must not rise above the dashed continuation of the τ vs. ϵ curve to $\epsilon < 2{\cdot}8$ eV. Figure 3 shows that this requirement is obeyed by all the known lines with the exception of λ4430 itself, which occurs very near the 2.8-eV break and may represent some other effect. If graphite particles are present in considerable quantity in the interstellar medium it will be interesting to see if any diffuse bands appear as a consequence in the region of high graphite transparency near 1500 Å.

F. M. Johnson (1966) has suggested that *complex molecules* containing C, H and N may be responsible for the diffuse bands. It may be that such heavy molecules do occur in the interstellar medium, because such compounds occur in comets, which some workers believe may have been captured by the Sun during a relatively recent encounter with an interstellar cloud. But no specific spectroscopic identifications of diffuse lines with molecules of high molecular weight have as yet been made.

I do not want to press these speculations. Such suggestions are interesting and attractive, but equally appealing ideas as to the carrier of the diffuse bands have been discredited before. In my opinion, what is needed to resolve these questions is, barring some dazzling flash of insight, more laboratory studies of plausible materials under interstellar conditions.

REFERENCES

Herbig, G. H. 1963, *Astrophys. J.*, **137**, 200.
Herbig, G. H. 1966, *Z. Astrophys.*, **64**, 512.
Herzberg, G. 1955, in *Les particules solides dans les astres*, Sixième Colloque int. Astrophys. Liège, *Mém. Soc. R. Sci. Liège*, 4ème Sér., **15**, 291.
Herzberg, G. 1965, *J. opt. Soc. Am.*, **55**, 229.
Johnson, F. M. 1966, *Bull. am. phys. Soc.*, Ser. II, **11**, 24; and private communication.
Nandy, K. 1964, *Publ. R. Obs. Edinburgh*, **3**, 137.
Stecher, T. P., Williams, D. A. 1966, *Astrophys. J.*, **146**, 88.
Underhill, A. B., Walker, G. A. H. 1966, *Mon. Not. R. astr. Soc.*, **131**, 475.
Van de Hulst, H. C. 1949, *Rech. astr. Obs. Utrecht*, **11**, part 2; see pages 30 and 47.
Walker, G. A. H. 1966, *Observatory*, **86**, 117.
Wilson, R. 1964, *Publ. R. Obs. Edinburgh*, **4**, 67.

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14. REMARKS ON THE DIFFUSE INTERSTELLAR LINES*

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ABSTRACT

It is suggested that the diffuse interstellar lines are produced in the interstellar gas by molecules consisting of a few hydrogen atoms and one other atom, such as CH_4^+ or NH_4. Diffuseness of the lines is assumed to result from predissociation of these molecules.

Most astronomers seem to believe, as does Herbig (Paper 13), that the diffuse interstellar lines are somehow produced by the interstellar dust. There are, however, some serious difficulties about this assumption, and therefore I have on various occasions (Herzberg 1955, 1965) emphasized the possibility that these interstellar lines might be due to negative ions or neutral molecules whose electron affinity or dissociation energy, respectively, is small enough that they can preionize or predissociate, and that in this way the diffuse nature of the lines can be accounted for. The beautiful spectra that Herbig has shown greatly strengthen my own belief that the predissociated spectrum of a polyatomic molecule present in the interstellar gas will be found responsible for the diffuse interstellar lines.

Under interstellar conditions each absorption band of a molecule consists only of one or two rotational components, and if predissociation is possible (and if the interaction with the continuum is not too strong), these lines would be symmetrically broadened. The great differences in line width observed for different interstellar lines are in accord with the variation of diffuseness observed in many cases of predissociation in the laboratory. As an example, Figure 1 illustrates two absorption bands of HCO in the region 6200 to 5500 Å. One of these bands consists of fairly sharp lines, the other of very diffuse lines. Although HCO is, of course, not responsible for the diffuse interstellar lines, its spectrum shows that diffuse lines of the right type and of greatly different width do occur for some molecules in the right spectral region.

The problem is to find the right molecule. Among the many possibilities only those molecules need be considered that have a sufficiently small dissociation energy ($D \leqslant 1{\cdot}8$ eV) and that are expected to have a strong absorption in the right spectral region. At the same time, of course, the molecule should be one that might be presumed to be reasonably abundant. In view of the great preponderance of hydrogen in the interstellar medium, it seems likely that the molecule in question contains no more than one atom other than hydrogen and as many hydrogen atoms as possible.

Considering the great abundance of CH_4 in the atmospheres of the outer planets (in addition to H_2), it does not seem impossible that it may be present in the interstellar medium. CH_4 is, however, very difficult to detect spectroscopically except in the infrared, and it is obviously not responsible for the diffuse interstellar lines because its dissociation energy is too large. However, the CH_4^+ ion is well known to have a small dissociation

*Invited introduction to the discussion of the preceding paper by G. H. Herbig.

energy, of the order of 1 eV, and it is readily formed by photo-ionization of CH_4 or by charge exchange of CH_4 with protons. On the basis of the electron configuration, an excited electronic state of CH_4^+ is expected at about 2 to 3 eV above the ground state. This state is anticipated to be a degenerate (^2E) state which would combine readily with the ($^2A_1$) ground state (the transition is somewhat similar to the well-known absorption of the iso-electronic NH_2 in the visible and red region of the spectrum). The vibrational structure of the $^2E-^2A_1$ transition may be rather complicated, because the E state is subject to a strong Jahn-Teller interaction and because there are six normal vibrations. This consideration may account for the fact that there are no obvious regularities among the twenty-six diffuse interstellar lines that Herbig has now established. It may, however, be mentioned that the separation of some of the principal lines is of the order of the predicted vibrational frequencies in such a molecule. Each vibration will have its own characteristic effect on the predissociation probability; thus the differences in line width are readily understood (Herzberg 1966).

Another molecule that may be worth considering is NH_4. Recent work by Bernstein (1963) and others has established that NH_4 is physically stable and has a dissociation energy of about 1 eV. Its electronic structure is similar to that of the Na atom; therefore a strong electronic transition is expected in the region of the sodium D lines, which is indeed the region in which many of the diffuse interstellar lines occur.

During the last two years, I have carried out a number of experiments aimed at finding the spectra of CH_4^+ and NH_4. Unfortunately, up to now these experiments have been unsuccessful. However, inability to produce these spectra in the laboratory does by no means disprove that these two molecules may be responsible for the diffuse interstellar lines.

R. Wilson (1964) has emphasized the fact that, if the diffuse interstellar lines are diffuse on account of predissociation or preionization of a suitable molecule or ion, the lifetime of the molecule in the interstellar radiation field is relatively short, and it is difficult to see how the molecules or ions can be formed fast enough. This argument against the interpretation of the diffuse interstellar lines as due to gaseous molecules or ions loses some of its strength by the observation of fairly high densities of OH in certain interstellar clouds, and also by the consideration that the CH molecule, which is known to be present in the interstellar medium, is subject to predissociation as has been shown by recent experiments in our laboratory. For these reasons I feel strongly that the search for molecules that might give rise to the diffuse interstellar lines in the gaseous phase should not be abandoned.

REFERENCES

Bernstein, H. J. 1963, *J. Am. chem. Soc.*, **85**, 484.
Herzberg, G. 1955, in *Les particules solides dans les astres*, Sixième Colloque int. Astrophys. Liège, *Mém. Soc. R. Sci. Liège*, 4ème Sér., **15**, 291.
Herzberg, G. 1965, *J. opt. Soc. Am.*, **55**, 229.
Herzberg, G. 1966, *Molecular Spectra and Molecular Structure. III. Electronic Spectra and Electronic Structure of Polyatomic Molecules*, Van Nostrand, Princeton, N. J.
Herzberg, G., Ramsay, D. A. 1955, *Proc. R. Soc. London Ser. A*, **233**, 34.
Johns, J. W. C., Priddle, S. H., Ramsay, D. A. 1963, *Disc. Faraday Soc.*, **35**, 90.
Wilson, R. 1964, *Publ. R. Obs. Edinburgh*, **4**, 67.

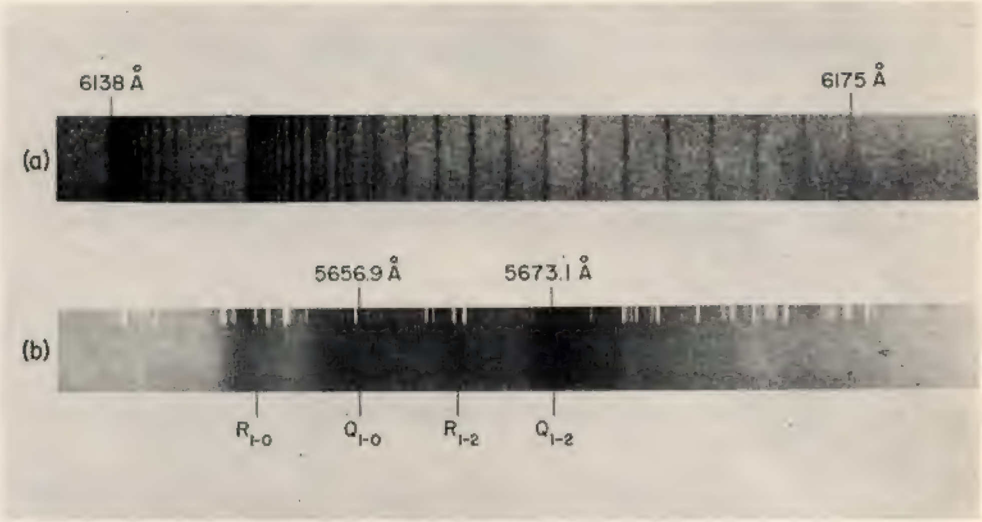

FIG. 1. Two absorption bands of HCO in the visible region:
(*a*) a band with sharp fine structure at 6138 Å (after Herzberg and Ramsay 1955);
(*b*) a band with diffuse fine structure near 5650 Å (after Johns, Priddle and Ramsay 1963).

Discussion

J. M. Greenberg: I have three comments on Herbig's paper (Paper 13).

(*a*) I understood you to say that the strength of λ4430 does not seem to depend on the presence of a hot star. Do you have any comment on the work of R. Stoeckly and K. Dressler (1964, *Astrophys. J.*, **139**, 240; see page 246), who find an anticorrelation between the strength of λ4430 and the presence of high-velocity components in the Ca II absorption, which would seem to indicate – indirectly – the presence or effect of hot stars?

(*b*) You consider the possibility of putting the source of the diffuse lines in small particles (0·03 μ in radius) and attributing the extinction – in the visible – to larger particles (radius 0·3 μ). I should mention that, if the material producing the diffuse lines is distributed in both small and large particles, it may be shown (J. M. Greenberg 1966, IAU Symposium no. 24) that it is not possible to get an absorption line *and* the proper extinction curve, even by adding large numbers of small particles. One gets instead a highly asymmetric dispersion line.

(*c*) I wonder what would happen if the small particles proposed by you were to form nuclei of the larger particles? You would certainly need the larger particles to shield the effect of all these core-particles.

G. H. Herbig answers:

(*a*) I have no comment on the findings of Stoeckly and Dressler. With regard to the effect on λ4430 of the presence of a nearby star, the observers themselves do not agree on the facts. I draw your attention to recent comments of G. A. H. Walker (1963, *Mon. Not. R. astr. Soc.*, **125**, 141) on this matter.

(*c*) I mentioned the possibility that the diffuse lines are associated with very small particles (if of ice, having radii of about 300 Å), purely because such particles avoid the problem of asymmetric and emission-winged absorption lines. Since they contribute little to the general extinction, such *ad hoc* particles can be inserted for my purpose with relative impunity. If the diffuse lines originate in such small, special particles, I suppose that as these small (and perhaps very young) particles grow by accretion of a mantle of frozen gases, their effectiveness for my purpose will decrease. You will recognize that this idea is quite similar to the Stoeckly-Dressler proposal, although I do not agree with their idea that λ4430 is due to a shift of Ca I λ4227, absorbed by calcium trapped in the particles. Their proposal can be tested directly when the next member of the Ca I series, λ2398, becomes accessible to space telescopes. Similarly I cannot go along with the suggestion of T. P. Stecher and D. A. Williams (1966, *Astrophys. J.*, **146**, 88; see page 102) that trapped CH radicals produce λ4430 by a similar shift of CH λ4300; the most important reason is that the two other band systems of CH (λ3140 and λ3900) are not accompanied by such diffuse bands.

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Chapter I C

Physical Processes in the Interstellar Medium

CHAIRMAN: L. Spitzer

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'The chief advantage of supernovae is that one is relatively free to make what assumption one wishes about the total energy. Factors of a hundred one can play around with . . .'

L. Spitzer, in the Discussion (Paper 23)

15. GENERAL CHARACTERISTICS OF INTERSTELLAR CLOUDS AND THEIR INTERPRETATION

(Introductory Report)

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ABSTRACT

This report is concerned with recent progress on various aspects of interstellar gas dynamics, including an investigation of the Orion Nebula, studies of H II regions and of ionization fronts, a statistical model of H I clouds and a re-appraisal of the heating and cooling processes in H I regions.

Dyson has worked out a new model for the Orion Nebula, in which it is supposed that dense pockets of non-ionized gas exist within the H II region. He makes predictions concerning the flow of ionized gas around these pockets, and about the possible presence of shock-waves nearby.

Mendis has extended Axford's classical description of ionization fronts to include the case in which a front advances into a region where the hydrogen is molecular, and finds that there are a number of consequent changes in the nature of the front. Hjellming has given a comprehensive account of the processes by which a thermal balance is achieved in an H II region, and has shown how the temperature in its various parts depends on the distance from the exciting star and on the stellar surface temperature. Mathews has integrated the equations of motion for a growing H II region, and has described how ionization fronts develop and when shocks will occur. Lasker has followed the motion further, and has given examples to show how older H II regions evolve.

By means of a simple model of H I clouds, Field and Saslaw have tried to estimate how long it would take to form a massive interstellar complex which would become gravitationally unstable. They find that the time required is relatively short. One must therefore assume that only a small fraction of an unstable cloud can condense into stars, or else the rate of star formation would be too rapid.

Finally an estimate is made of the rate at which early-type stars supply kinetic energy to the H I clouds, via the expansion of H II regions. One cannot, with the present data, decide definitely whether this process is important. A possible alternative would be the acceleration of gas clouds by supernova shells.

1. INTRODUCTION

It is generally thought that about 10% of the interstellar hydrogen is ionized, and that the remainder is non-ionized. Nevertheless, much more successful theoretical work has been done lately on problems relating to H II regions. There seem to be a number of explanations for this discrepancy. The observations show much more detail of H II regions, their energy balance is easier to understand, and most probably they are hardly influenced by magnetic fields.

On the other hand it is difficult to obtain detailed information on H I clouds, their energy balance is still obscure, and magnetic fields may or may not be important in their dynamics. The choice of subjects in this review reflects this imbalance in our understanding, in that rather more attention will be given to recent theoretical work on H II regions.

2. THE ORION NEBULA: A MODEL WITH A SMOOTH DISTRIBUTION OF ELECTRON DENSITY

The Orion Nebula is probably the most interesting and best observed of the H II regions. It is excited by some half dozen early-type stars, among them an O6 and an O9 star. Menon (1961) finds that the radiation of these stars in the Lyman continuum is more than enough to keep the nebula ionized, provided its gas density varies smoothly, and there are no dense pockets of hydrogen inside it.

Menon has gone on to construct a *density profile* for such a nebula. He has somewhat idealized its structure by assuming it to be spherically symmetrical, but this probably will not have too serious an effect on the order of magnitude of the important physical parameters deduced. The density profile is readily found from observations of the integrated emission of the nebula in the radio continuum. Menon's observations were made at a wavelength $\lambda = 3{\cdot}75$ cm. He had to assume a temperature, and, as is usual in studies of H II regions, took this to be 10 000 °K. The inferred density profile is shown in Figure 1. It appears there that the density decreases sharply from the centre outwards, with the steepest decrease near the centre. To obtain a linear scale for the density variation one has to know the distance from the Sun to the Orion Nebula; this is usually taken to be 450 pc, so that one minute of arc corresponds to 0·13 pc.

The broken curve sketched in Figure 1 describes a Gaussian distribution of electron density

$$n_e = 2{\cdot}69 \times 10^3 \exp\{-r^2/r_*^2\} \quad , \tag{1}$$

with $r_* = 0{\cdot}4$ pc, approximately, and gives a reasonable fit to the observations for the innermost part of the nebula. But the smallness of the value of r_* immediately raises a problem. Assuming the gas to be isothermal at 10^4 °K one finds that the pressure p is given by

$$p = 2n_e kT. \tag{2}$$

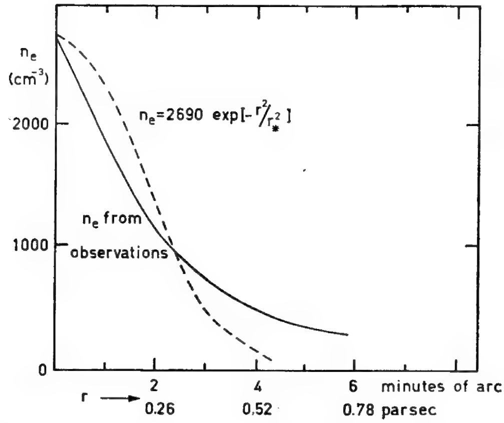


FIG. 1. Density distribution in the Orion Nebula. The continuous curve shows the variation of electron density with radial distance, as derived by Menon (1961) from radio observations. The broken curve shows the form of the idealized variation, assumed in the calculation in Section 2. (Diagram from Dyson 1966)

The outward acceleration due to the *pressure gradient* becomes

$$f = -\frac{1}{\rho}\frac{dp}{dr} = -\frac{2kT_e}{m}\frac{d}{dr}(\ln n_e) = \frac{2c_i^2}{r_*^2}r. \tag{3}$$

Expression (1) has been used here to describe the electron density, and $c_i \equiv (2kT_e/m)^{1/2}$ equals the isothermal speed of sound in the ionized gas. If the nebula contained a uniform distribution of gravitating matter, the outward acceleration due to the pressure gradient might, perhaps, be balanced by gravitation. The density ρ_M required to make the gravitational field strong enough is given by

$$\frac{4\pi}{3}G\rho_M = \frac{2c_i^2}{r_*^2}. \tag{4}$$

Now on this model $r_* = 1{\cdot}2 \times 10^{18}$ cm and $c_i^2 = 1{\cdot}7 \times 10^{12}\ \mathrm{cm^2\,sec^{-2}}$, so that

$$\rho_M = 10^{-17}\ \mathrm{g\,cm^{-3}} = 1{\cdot}5 \times 10^5\, M_\odot\, \mathrm{pc^{-3}}.$$

There is no evidence that such a high density of matter exists in the inner regions of the Orion Nebula. If the electron density has been found correctly from the observations, then the ionized gas cannot be kept in equilibrium. Instead *the nebula must expand*; in a regions where formula (1) describes the electron density, r_* would be a function of time. One can go on to work out a *maximum age* for an H II region having now a density profile such as that in formula (1).

Under the given pressure gradient, the acceleration is everywhere proportional to the distance r of the element from the centre of the nebula, at any one time. The distribution of ionized gas therefore maintains its shape as it expands, and its linear scale varies like r_*. One finds that

$$\ddot{r}_* = \frac{2c_i^2}{r_*}, \tag{5}$$

so that

$$\dot{r}_* = 2c_i\sqrt{\ln (r_*/R_*)} \ . \tag{6}$$

It has been assumed here that the motion started from rest at time $t = 0$, when r_* had the value R_*. At that time the nebula had just been suddenly ionized. With the substitution

$$\theta = \sqrt{\ln (r_*/R_*)}$$

one can integrate equation (6) to obtain

$$t = \frac{r_*}{c_i} \exp(-\theta^2) \int_0^\theta \exp(u^2)\, du. \tag{7}$$

The function of θ on the right-hand side of this equation is called Dawson's integral, and tables of its values are given, for example, by Abramowitz and Stegun (1965). The maximum value of the integral is 0·541. The maximum time t_m that can have elapsed since the original ionization is therefore given by

$$t_m = 0{\cdot}541\, r_*/c_i = 17\,000 \text{ years.}$$

In this estimate r_* has been put equal to 0·4 pc and c_i to 13 km/sec.

Such a model makes *impossible demands*. It implies that all the stars which are now exciting the nebula moved onto the main sequence in a time of at most this order, and this is very unlikely. The same result would follow from more elaborate calculations. Thus Vandervoort (1963) studies in detail the motion of the H II region, beginning from a density distribution like that of a self-gravitating H I cloud in equilibrium. He shows that the ionization front produced after the stars begin to shine must be of extreme weak R-type. This is due to the very great luminosity of these early-type stars in the Lyman continuum. The ionization front thus moves outwards at a highly supersonic speed. Its passage would cause hardly any immediate change in the motion of the gas. It would simply leave the gas very much hotter and in a state of great pressure imbalance. The resulting pressure gradient sets up the motion. Vandervoort goes on to calculate the properties of his model of the nebula, and finds results quite similar to the ones described here.

3. THE ORION NEBULA: A MODEL INCLUDING GLOBULES OF NON-IONIZED GAS

The assumption of a smooth electron-density distribution evidently leads to great difficulties in finding an acceptable age for the Orion Nebula. It is therefore worth noting that the observations do not, in fact, directly involve the electron density n_e. The rate of radiation in the radio continuum depends on n_e^2, the square of the electron density. The same applies to the intensity of the Balmer lines, and of the radio spectral lines due to transitions between adjacent high-excitation states of the hydrogen atom. Strictly speaking the ordinate in Figure 1 should be $\langle n_e^2\rangle^{1/2}$. If the electron density in the nebula fluctuates over distances which cannot be resolved, $\langle n_e^2\rangle^{1/2}$ may be very much larger than $\langle n_e\rangle$.

The very large pressure gradient which was inferred in Section 2 depends on the presence of a large gradient in $\langle n_e\rangle$. Suppose that the *fluctuations in electron density*

are much more pronounced near the centre of the nebula than near the edge. It would then be possible for $\langle n_e^2 \rangle^{1/2}$ to have a strong gradient outwards, in accordance with observation, but there need not be a large drop in the mean pressure. If so, there is no theoretical basis for our age determination of the nebula. Dyson (1966) has recently studied the consequences of assuming that the Orion Nebula contains many *globules of cool non-ionized gas*. The typical globule is assumed to have a mass of the order of a solar mass and a radius of the order of 10^{16} cm. Within the globule the gas is assumed to be isothermal, at 100 °K. This is a simplification, made to ease the calculation; in a more realistic model the thermal balance in the globule would have to be considered more carefully. Self-gravitational effects are found to be important, and therefore the globule is treated like an isothermal Emden gas sphere.

At the boundary of the globule there will be a D-critical *ionization front* (I-front). This advances subsonically into the non-ionized gas. The ionized gas streams away outwards at the (isothermal) speed of sound corresponding to 10^4 °K, the temperature in the H II region. On this model the density of the ionized gas near the I-front will be as high as 10^5 or 10^6 electrons (and ions) per cm³.

Dyson simplifies his calculation by assuming spherical symmetry for the globule and for the radiation field in which it is bathed. In propagating from infinity to the globule, the *incident radiation is attenuated in the Lyman continuum*. The amount of attenuation can easily be calculated if one knows the electron (or ion) density n_i in the ionized gas as a function of r, the distance from the centre of the globule. The density in turn may be found as follows.

The globule has mass M and radius R_i; the atomic weight and the temperature of the gas are assumed to be known. There is only one Emden sphere which fits the boundary conditions. In particular there are unique values for the parameter

$$x_i \equiv \frac{R_i}{c_n} (4\pi G \rho_c)^{1/2} , \tag{8}$$

and for the density and pressure of the non-ionized gas just inside the boundary. (Here ρ_c is the central mass density of the globule, and c_n the isothermal speed of gas in the non-ionized gas.) The D-critical condition fixes the value of $N_i \equiv n_i(R_i)$, and also ensures that the initial velocity of the ionized gas is c_i.

One can readily calculate the density, n_i, and the velocity, u_i, of the ionized gas at any point outside the globule. In a steady flow the equation of motion is

$$u_i \frac{du_i}{dr} = -\frac{1}{\rho}\frac{dp}{dr} = -c_i^2 \frac{d}{dr}(\ln n_i). \tag{9}$$

There is no term corresponding to gravitational acceleration on the right-hand side, because the ionized gas is too hot for gravitational effects to be important.

The equation of continuity integrates to give

$$n_i u_i r^2 = N_i c_i R_i^2 . \tag{10}$$

It follows from (9) and (10) that

$$\tfrac{1}{2}u_i^2 - c_i^2 \ln(u_i/c_i) = \tfrac{1}{2}c_i^2 + 2c_i^2 \ln(r/R_i). \tag{11}$$

Equations (10) and (11) determine the run of u_i and n_i with r. In particular the electron density, n_i, can be found as a function of position, and with its help one determines J_f, the photon flux at the I-front, in terms of J_∞, the flux at infinity. This leads to a relation between M, R_i and J_∞, owing to the condition that the photon flux J_f must be just right to make the flow across the I-front D-critical. *Two parameters thus specify the state of any globule in the radiation field*; the most convenient pair are J_∞ and x_i. If the distant radiation field remains unchanged, i.e., if the exciting stars evolve relatively slowly, then only the parameter x_i varies from globule to globule, or as a globule evolves. It turns out that for a given J_∞ there is a *maximum mass* that a globule can have. It is attained when $x_i = 6{\cdot}14$.

Any globule must change with time because its mass is continually being reduced by ionization. Given a fixed value for J_∞, a decrease in the mass M of a globule leads to a decrease or an increase in x_i, according as $x_i \lessgtr 6{\cdot}14$. As they lose mass, globules with $x_i < 6{\cdot}14$ therefore evolve in the direction of decreasing central condensation. Such globules will provide a long-lasting *source of high-density ionized gas*, until they have been completely eaten away. Their lifetimes are of the order of several tens of thousands of years, per solar mass.

A globule with $x_i > 6{\cdot}14$ would evolve in the direction of increasing central condensation, and would certainly become *gravitationally unstable* when x_i became equal to $6{\cdot}5$. But it may well be that such globules are unstable in any case. This point needs to be investigated further. Possibly the unstable globules collapse, eventually to form stars.

4. VELOCITY DISCONTINUITIES IN THE ORION NEBULA

A collection of globules of non-ionized gas produces streams of ionized gas with a very non-uniform density. Each stream accelerates away from its globule. Equation (11) may be used to find the stream velocity u at a distance r from the centre of the globule. To a good approximation

$$u = c_i\{1 + 4\ln(r/R_i)\}^{1/2}\left[1 + \frac{\ln\{1 + 4\ln(r/R_i)\}}{8\ln(r/R_i)}\right], \tag{12}$$

provided r/R_i is not too close to unity. Some values of u are shown in Table 1; once again $c_i = 13$ km/sec.

Table 1

Stream velocity u of ionized gas at a distance r from a globule of radius R_i

r/R_i	u/c_i	u (km/sec)
10	3·70	48·1
20	4·00	52·0
100	4·75	61·8

It is expected that there are many globules in the nebula. The presence of the other globules has little influence on the flow of the ionized gas at a small distance r from a given globule. But eventually there is bound to be a splash when the stream from one globule runs into that from another. Dyson has studied the nature of the *interaction*

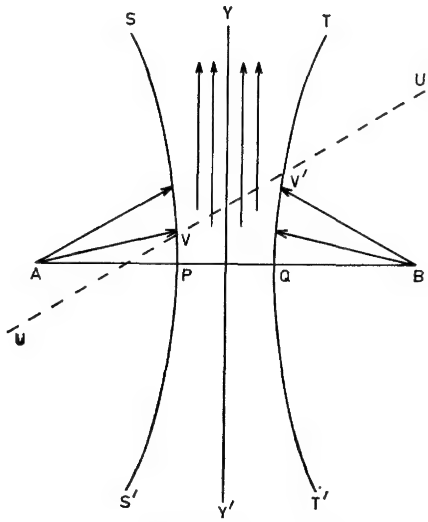


FIG. 2. A splash in an H II region. The ionized gas flows out radially from two globules, centred at A and B. The curves SPS′ and TQT′ indicate the location of the two shocks that form in the flow. In the layer between the shocks the gas density is higher, and the direction of flow is nearly parallel to YY′. UVV′U′ represents a typical line of sight through the flow region. (Diagram after Dyson 1966)

between the streams coming from two identical globules, which are centred at points A and B, a distance $2D$ apart. A reasonable value for D would be about $20R_i = 2 \times 10^{17}$ cm, say. The resulting flow pattern has axial symmetry about the line AB. A plane section through the pattern is sketched in Figure 2.

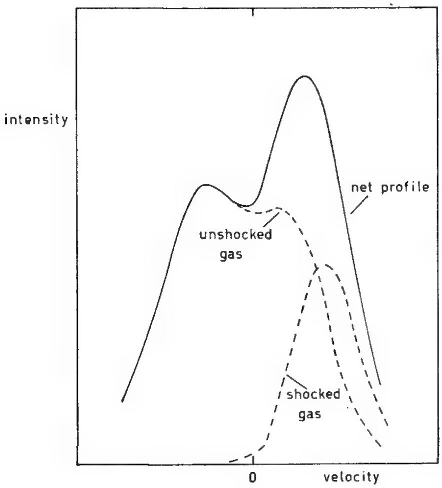
Two curved shocks will form; their sections are shown in the figure by the curves SPS′ and TQT′. The shocks will be isothermal, since the temperature throughout the H II region is controlled by radiative rather than dynamical processes. But the density will be higher in the shocked layer than outside it, by a factor of the order of $(u/c_i)^2$, or about 16, according to our figures. This change affects the ionization balance in the shocked region.

Knowing the flow pattern and the ionization balance one can predict the *shapes of emission lines* seen along lines of sight which cut through the sandwich. Figures 3a and 3b show some typical results calculated by Dyson. Note the difference between the appearances of the lines due to the O^+ and the O^{++} ions. This is due to the fact that O^+ ions are found preferentially in the high-density region of the shocked gas.

The predicted line shapes and the differences between the [O II] and [O III] lines agree well with the spectra observed by Wilson *et al.* (1959). It seems likely that the line splitting noted by them is due to the existence in the Orion Nebula of splashes such as Dyson has described.

5. DISSOCIATION-IONIZATION FRONTS

Most work on ionization fronts is based on the assumption that the non-ionized hydrogen is largely present in atomic form. But in regions where the gas density is high



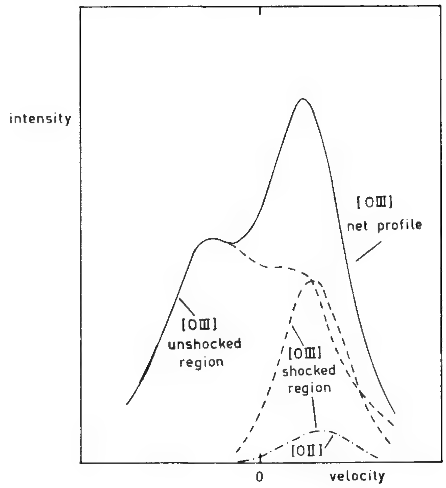


FIG. 3a. Typical profile for a Balmer line, seen in emission through the flow region in Figure 2. (Diagram from Dyson 1966)

FIG. 3b. Typical profiles for [O III] and [O II] lines. Note that the emission of [O II] lines is virtually limited to the shocked region. (Diagram from Dyson 1966)

and the temperature low, it is quite possible that the hydrogen will be *molecular*. If so, both dissociation and ionization must take place in the front.

The dissociation energy for molecular hydrogen is about 4.5 eV. Any shock wave travelling ahead of a front will heat the gas to a few times ten thousand degrees Kelvin, corresponding to an energy of the order of 1 eV per degree of freedom. In the process some molecules might gain sufficient vibrational energy actually to dissociate. But the process is slow, there are many cooling mechanisms competing for the energy, and in any case there is not enough energy available to dissociate more than a fraction of the H_2 molecules present. The possibility of *predissociation may therefore be neglected*. Mendis (1967), in his recent work on dissociation, has accordingly assumed that radiative processes will dominate. We shall now discuss some of his results.

Mendis finds that *the dissociation front cannot separate from the ionization front*. This conclusion may be derived from the following argument. The radiative reactions leading to the destruction of molecular hydrogen are

$$(i) \qquad H_2 + h\nu_1 \rightarrow H + H^* \qquad (h\nu_1 > 14{\cdot}7 \text{ eV})$$

and

$$(ii) \qquad H_2 + h\nu_2 \rightarrow H_2^+ + e. \qquad (h\nu_2 > 15{\cdot}4 \text{ eV})$$

Reaction (*i*) produces two hydrogen atoms, one of which will be in the ^2P state; reaction (*ii*) produces an electron, and an H_2^+ ion in the $^2\Sigma_g^+$ state. Both reactions require radiation in the Lyman continuum ($h\nu > 13{\cdot}6$ eV). Such photons cannot penetrate into regions containing appreciable quantities of atomic hydrogen in the line of sight. It follows that the processes (*i*) and (*ii*) cannot take place too far ahead of the ionization front. In fact the dissociation and ionization fronts amalgamate.

In the case of the ionization fronts studied by Dyson, and in many others, there is a large optical depth τ_L at the Lyman limit between the exciting star(s) and the front. At a frequency ν in the Lyman continuum, the hydrogen atom has an absorption cross-section $2{\cdot}5 \times 10^{-29}\nu^{-3}$. The optical depth τ at frequency ν is therefore $\tau_L(\nu_L/\nu)^3$, where ν_L is the frequency at the Lyman limit. If the exciting star radiates like a black body at temperature T_*, the distribution of frequencies absorbed is, for $h\nu \gg kT_*$, governed by the factor $\exp\{-(\tau_L\nu^3/\nu^3 + h\nu/kT_*)\}$, which peaks at the frequency

$$\nu_m = \nu_L \left(\frac{3kT_*}{h\nu_L}\tau_L\right)^{1/4}. \tag{13}$$

In a typical case one might have $T_* = 5 \times 10^4$ °K and $\tau_L = 8$, say, and then $\nu_m/\nu_L = 1{\cdot}7$. The maximum rate of absorption of photons will occur at an energy of about $h\nu_m = 23{\cdot}2$ eV. It exceeds the rate at the Lyman limit by a factor

$$\exp\{\tau_L + h\nu_L/kT_* - 4(h\nu_L/3kT)^{3/4}\,\tau_L^{1/4}\} \quad ,$$

or about 75 with the values assumed above. Consequently only a fraction of a per cent of the photons reaching the front will have energies between the Lyman limit and 15.4 eV, the minimum needed for reaction (*ii*). Thus the calculation can be simplified by the assumption that *any photon which can ionize atomic hydrogen will also ionize and/or dissociate molecular hydrogen*, and there can be (practically) no molecular hydrogen inside the H II region. Another consequence is that the average photon absorbed at any ionization front usually has rather more energy than the average photon in the Lyman continuum emitted by the exciting star. This hardening of the radiation is also important in some of the work done by Hjellming, by Lasker and by Mathews, which we shall describe in Section 6.

We return to the discussion of the likely *reactions*. The ionization of molecular hydrogen, process (*ii*), can be followed by

(*iii*) $\quad H_2^+ + h\nu_3 \rightarrow H + H^+, \qquad (h\nu_3 > 2{\cdot}5\ \text{eV})$

(*iv*) $\quad H_2^+ + e \rightarrow H + H,$

or (*v*) $\quad H_2^+ + H_2 \rightarrow H_3^+ + H.$

Rough estimates suggest that reaction (*iv*), the dissociative recombination of the H_2^+ ion, is usually much faster than reaction (*iii*), the dissociation of the H_2^+ ion. It seems permissible, accordingly, to neglect reaction (*iii*). The outcome of (*ii*) followed by (*iv*) is the same as the outcome of (*i*): in either case an H_2 molecule is dissociated. The process (*v*), however*, leads to the formation of an H_3^+ ion, at a rate which is not known. Most probably (*iv*) is rather faster than (*v*), except very far upstream in the front, where H_2 molecules are much more abundant than electrons. Therefore, a quantity of H_3^+ ions may form. Their later fate is hard to determine, since there are at present no data on the reactions into which H_3^+ is likely to enter.

The curves in Figure 4 describe the *structure of a dissociation-ionization front*, as computed by Mendis. This particular front is of weak R-type, and the computation allows for the conditions of continuity, momentum and energy balance. The cooling of the

*Dr. G. Herzberg drew my attention to this reaction during the Symposium. See Herzberg's remarks in the discussion (Paper 23).—F.D.K.

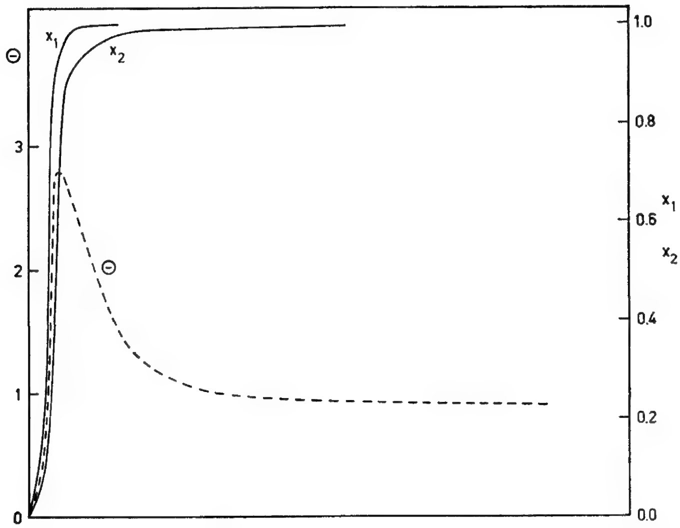


FIG. 4. A structure of a weak R-type dissociation-ionization front, as calculated by Mendis. The abscissa denotes distance. The curves depict the variation of x_1, x_2, the fractional dissociation and ionization, and of θ, the temperature in units of 10^4 °K.

front is assumed to be due to O^+ ions, just as it was in the ionization fronts studied by Axford (1961). The curves show clearly how the processes of ionization ($x_2 \to 1$) and dissociation ($x_1 \to 1$) occur in overlapping regions.

The *properties of ionization fronts advancing into atomic hydrogen* have been discussed in detail by Axford. He remarks that there is an invariant relationship between the two quantities G and Y. G, the normalized stagnation enthalpy, is proportional to $\{(\gamma + 1)/(\gamma - 1)\}p/\rho + u^2/2$, in a gas whose ratio of specific heats is γ, and Y is proportional to p/ρ. The $G(Y)$ relation is

$$G = 1 + \frac{1}{2}\left(\frac{\gamma + 1}{\gamma - 1}\right) Y \pm \sqrt{1 - Y}, \tag{14}$$

and is sketched in Figure 5. Points on the curve between O and K correspond to subsonic flow, and points between K and P to supersonic flow.

In a monatomic gas, $\gamma = 5/3$, and G has a maximum value $G_{max} = 25/8$. This severely restricts the class of possible strong D-type fronts. Such fronts begin upstream on the lower branch of the $G(Y)$ curve, and end downstream on the K P branch. The transition is possible only via the point K. Thus the normalized enthalpy G must reach exactly the maximum value 25/8 somewhere within the ionization front.

In a *dissociation-ionization front* this result applies no longer. The particles upstream are now diatomic, and have $\gamma = 7/5$, but downstream they are electrons and protons, and have $\gamma = 5/3$. Within the front the effective value of γ lies between these limits, depending on the degree of dissociation. For $\gamma = 7/5$, G_{max} equals 49/12. In the case of a dissociation-ionization front one only knows that G must pass through a maximum

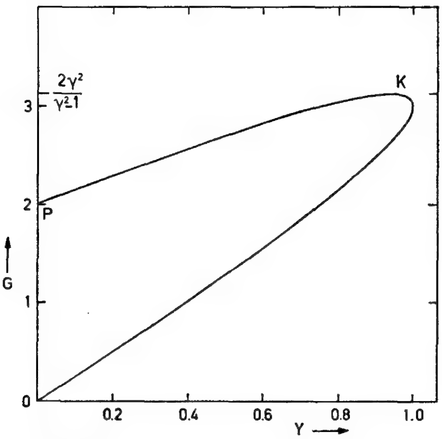


FIG. 5. Variation of G with Y. For details see text.

value which lies between 25/8 and 49/12. This condition is much less restrictive. It follows that *strong D-type dissociation-ionization fronts can occur more readily than the corresponding simple ionization fronts.*

6. BETTER MODELS OF H II REGIONS

Early theoretical models of H II regions, calculated by Goldsworthy (1961) and Axford (1961), incorporated dynamical effects and allowed for heating and cooling by means of some simple, approximate formulae. To make his work possible Goldsworthy had to restrict his investigations to gas spheres with a rather singular initial density distribution, so that the later motion could be described by a *similarity solution.* The resulting configuration then had an invariant shape in every case, and only its scale would change with time. He also had to assume that the star exciting the H II region had begun to shine suddenly, and had radiated with a constant luminosity thereafter. Because the initial mass distribution of the gas had a strong peak at the centre, it was almost inevitable that a large pressure gradient was predicted for the newly-formed H II region. The ionized gas from the inner regions would then tend to overtake the ionized gas further out, and consequently shock waves tended to form in all these models. Shock waves may or may not form in real H II regions.

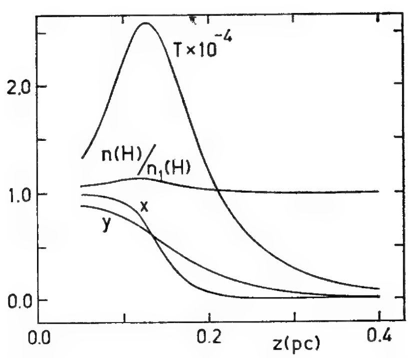
The development of computers since then has made it possible to carry out more realistic calculations, in which the physical conditions are better described, and which need not be restricted to configurations that will lead to similarity solutions. These advances are presented in three important papers, by Hjellming (1966), Lasker (1966), and Mathews (1965).

a. The work of Hjellming (1966)

Hjellming allows for the *ionization of helium* as well as hydrogen. Radiation shortward of the wavelength 504Å can ionize helium, and will not penetrate beyond the boundary of the He II region. This affects the rate of heating of the ionized gas and the state of ionization of some of the possible coolants. In the He II region the important cooling

particles will be O^{++}, Ne^{++}, N^{++}, and N^{+++}, and of these O^{++} will be the most important; elsewhere O^{+}, N^{+} and Ne^{+} ions will be important, and the two latter will dominate unless the temperature exceeds 10^4 °K. Hjellming calculates the temperature to be expected in an H II region, given the temperature of the exciting star. In general the temperature rises from the centre outwards. It has a value between 4000 and 6000 °K near the star, and between 8000 and 10 000 °K near the boundary. The positive temperature gradient is due to the hardening of the radiation, described in Section 5. Just inside the ionization front the optical depth τ_L at the Lyman limit reaches quite large values, ranging from 3·5 to 8 for stars with temperatures between 3×10^4 and 5×10^4 °K.

The *structure of an ionization front* can then be calculated, so as to fit onto the H II region within. Hjellming gives some examples of weak R-type and weak D-type fronts. The gas flows supersonically through the former and subsonically through the latter. The speed of passage through an R-type front is so great that the heat released on ionization cannot at first be balanced by the cooling processes. The temperature in the gas then rises to 25 000 °K, or even higher, in a rather thin layer, beyond which it falls to the equilibrium value for H II regions. But in D-type fronts the speed is low, and the temperature increases smoothly and almost monotonically from its equilibrium value on the H I side to its equilibrium value on the H II side. A pronounced density drop occurs near the leading edge of a weak D-type front, because the gas pressure must remain almost uniform in the subsonic flow. But the flow is supersonic through a weak R-type front, there is no time for the gas to redistribute itself, and so its density remains almost unchanged. These results are illustrated in Figures 6 and 7.



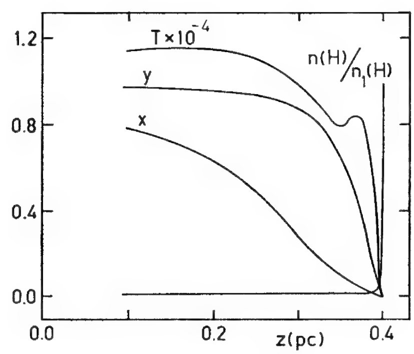


FIG. 6. The structure of a weak R-type ionization front (Hjellming 1966), for a model with the following parameters: effective temperature of exciting star, $T_e = 40\,000$ °K; velocity of neutral gas relative to ionization front, $v_1 = 50$ km/sec; hydrogen concentration in the neutral gas ahead of the ionization front, $n_1(\mathrm{H}) = 10\ \mathrm{cm}^{-3}$; helium abundance, $n(\mathrm{He})/n(\mathrm{H}) = 0{\cdot}15$. The following quantities are plotted: T, gas temperature; $n(\mathrm{H})/n_1(\mathrm{H})$, hydrogen concentration relative to that in the neutral gas ahead of the ionization front; x and y, fractional ionization of hydrogen and helium, respectively. The spatial coordinate along the direction of motion of the front is denoted by z. (Adapted from *The Astrophysical Journal.*)

FIG. 7. The structure of a weak D-type ionization front (Hjellming 1966), for a model with the following parameters (cf. Figure 6): $T_e = 50\,000$ °K, $v_1 = 0{\cdot}02$ km/sec, $n_1(\mathrm{H}) = 500\ \mathrm{cm}^{-3}$, $n(\mathrm{He})/n(\mathrm{H}) = 0{\cdot}15$. Quantities plotted as in Figure 6. (From *The Astrophysical Journal.*)

b. The time evolution of an H II *region (Mathews 1965)*

The calculation by Mathews is designed to exhibit *evolutionary effects during the growth of an* H II *region.* In order to simplify the description of the thermal processes, he approximates the actual cooling rate of the gas by a quadratic formula, but allows for the hardening of the Lyman continuum radiation with optical depth. The H II region considered by him is excited by a star having a mass of 30 $M_\odot$. Before ionization the density of the interstellar gas near the star is assumed to be uniform. The calculation shows how the H II region grows, as the star evolves onto the main sequence and then remains there. In particular Mathews shows the radial variation, at three different times, of the density, temperature, velocity and fractional ionization of the gas (Figures 8, 9 and 10). The results confirm that *little motion occurs in the gas in the early stages* of the ionization, and that later velocities of a few km/sec develop near the ionization front. (But note that the initial density distribution in Mathews' model is uniform, in contrast to the non-uniform distribution assumed for the simple model of the Orion Nebula, which we described in Section 2.) Eventually a shock forms near the head of the ionization front.

Mathews shows particularly well that the *transition between* H I *and* H II *regions always takes place very sharply*, in a layer having a thickness of only two or three per cent of the radius of the H II region. This result justifies the usual approximation that ionization fronts are thin, and that their curvature may be neglected in a calculation to determine their structure.

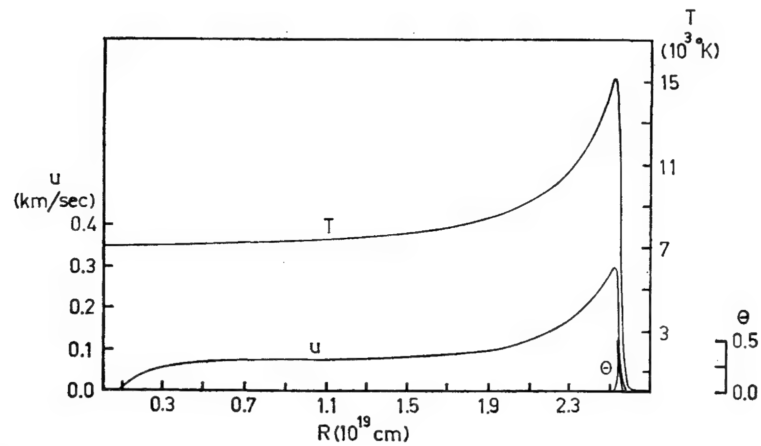


FIG. 8a. Gas velocity u, temperature T, and ionization parameter θ, as functions of radius R at $t = 0{\cdot}919 \times 10^4$ years. The ionization parameter is defined as $\theta \equiv \frac{1}{2} - |x - \frac{1}{2}|$, with x the fractional ionization of hydrogen. (Mathews 1965, adapted from *The Astrophysical Journal.*)

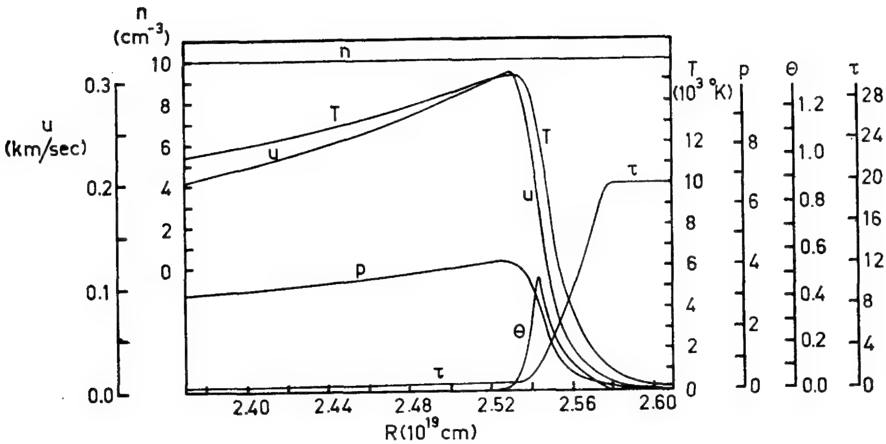


FIG. 8b. Variation of velocity u, number density n, temperature T, ionization θ, pressure p, and optical depth τ in the vicinity of the ionization front after $0{\cdot}919 \times 10^4$ years. This figure is a partial enlargement of Figure 8a. (Mathews 1965, adapted from the *Astrophysical Journal*.)

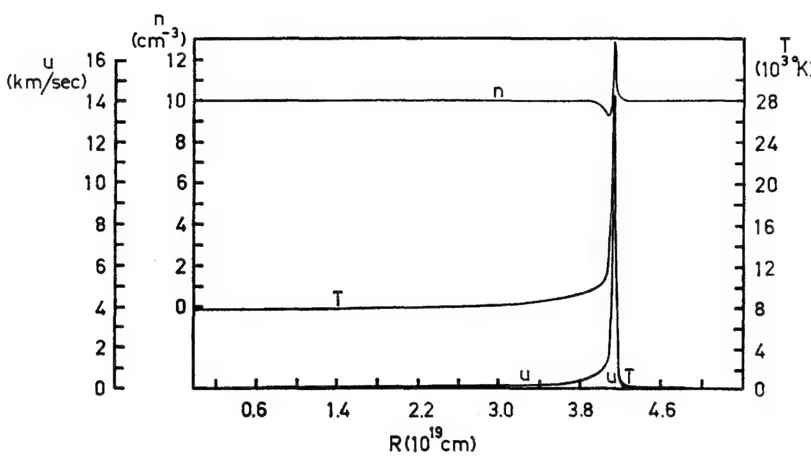


FIG. 9a. Gas velocity u, number density n, and temperature T, as functions of radius R after $3{\cdot}07 \times 10^4$ years. (Mathews 1965, adapted from *The Astrophysical Journal*.)

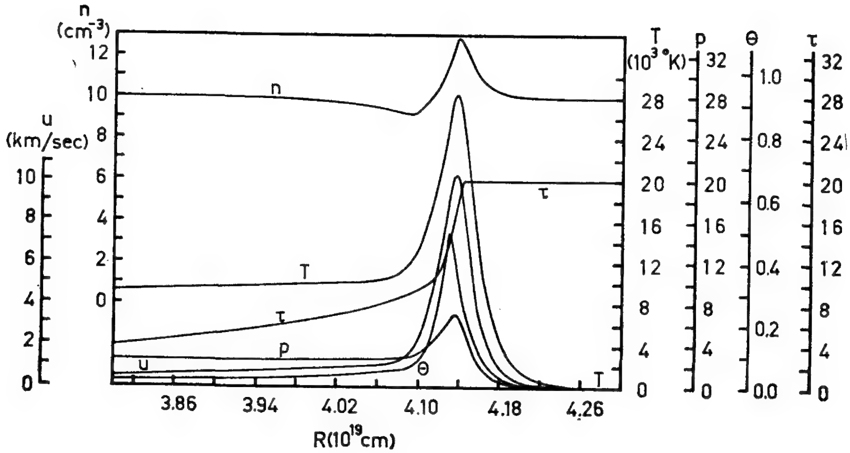


FIG. 9b. Variation of velocity u, number density n, temperature T, ionization parameter θ, pressure p, and optical depth τ in the vicinity of the ionization front at $t = 3{\cdot}07 \times 10^4$ years. (Mathews 1965)

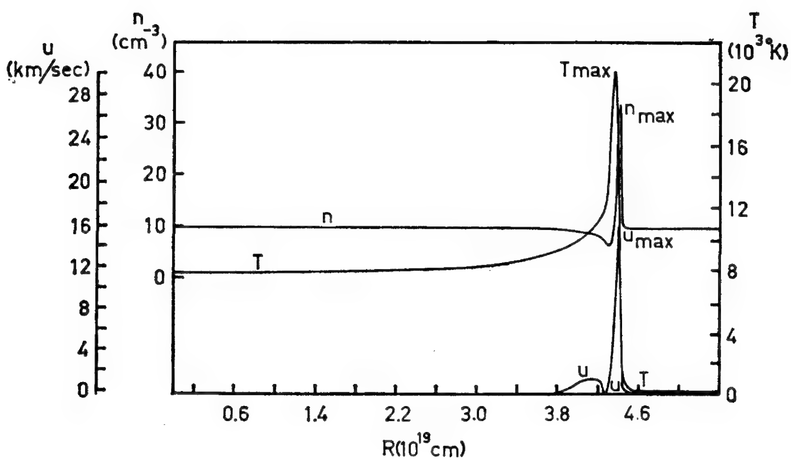


FIG. 10a. Gas velocity u, number density n, and temperature T as functions of radius R at $t = 6{\cdot}16 \times 10^4$ years. (Mathews 1965, adapted from *The Astrophysical Journal*.)

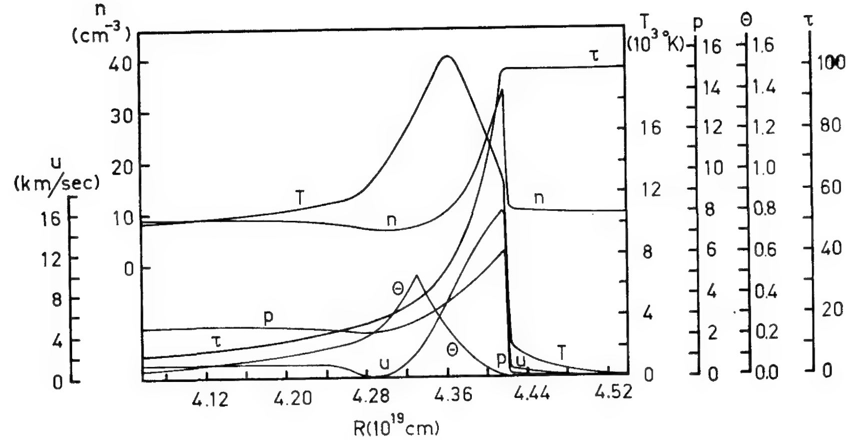


FIG. 10b. Variation of velocity u, number density n, temperature T, ionization parameter θ, pressure p, and optical depth τ in the vicinity of the ionization front after $6{\cdot}16 \times 10^4$ years. (Mathews 1965)

c. The dynamics of old H II *regions* (*Lasker 1966*)

Finally Lasker aims at describing the *evolution of an* H II *region over rather longer intervals of time*. His assumptions are that the gas in the H II regions remains at a temperature of 10^4 °K throughout, and that the gas in the H I region outside may be heated on passing through a shock, and will later be cooled. Various cooling rates are postulated in different cases, but it makes little difference which of them is used. Changing the cooling rate really affects only the thickness of the shocked H I layer outside the ionization front. In any case the thickness of this region is always small in comparison with its radius.

Just as Mathews did, Lasker finds that the ionization front is at first of weak R-type, and that a shock develops sometime later. It moves ahead of the ionization front, which becomes weak D-type. A partial vacuum begins to form in the H II region, and the density falls to as little as one-tenth of its initial value. Most of the gas concentrates into the shocked H I layer, and the density there becomes three or four times its initial value (this is the case without cooling in the H I region).

A result of particular interest is Lasker's estimate for the *total energy communicated to the neutral hydrogen gas*. For his hypothetical O7 star this energy is of the order of 10^{49} erg.

Lasker also describes the evolution of H II regions in *clouds which initially have a density that is high at the centre and decreases outwards*. After a million years of illumination by an O star the resulting structures are barely distinguishable from H II regions which have grown in clouds of initially uniform density.

Some of Lasker's results are illustrated in Figures 11 and 12.

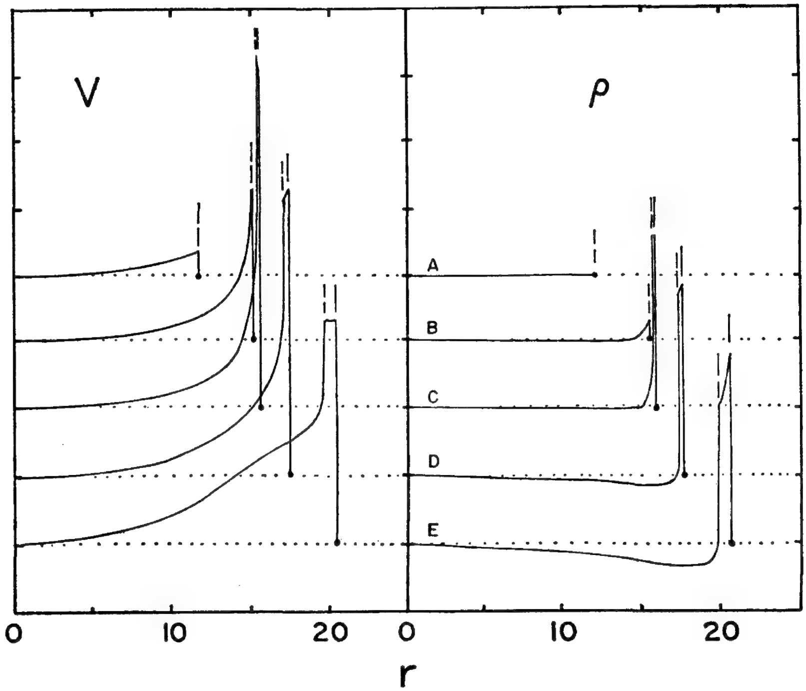


FIG. 11. The younger models for H II regions having an initial density of $6{\cdot}4\ \mathrm{cm}^{-3}$. The broken and the continuous vertical lines mark the positions of the I-front and of the shock, respectively. The marked vertical units are $0{\cdot}25\ c$ for the v-scale and ρ_0 for the ρ-scale; r is in parsecs, v is the velocity of the gas, ρ is its density, ρ_0 the initial density, and c the speed of sound. The heavy dots in which the curves are terminated mark the ordinates for $v = 0$ and for $\rho = \rho_0$ for each model. Models A–E apply to ages of $2{\cdot}2 \times 10^4$, $7{\cdot}8 \times 10^4$, $9{\cdot}0 \times 10^4$, $1{\cdot}8 \times 10^5$, and $3{\cdot}6 \times 10^5$ years, respectively. (Lasker 1966, reproduced from *The Astrophysical Journal*.)

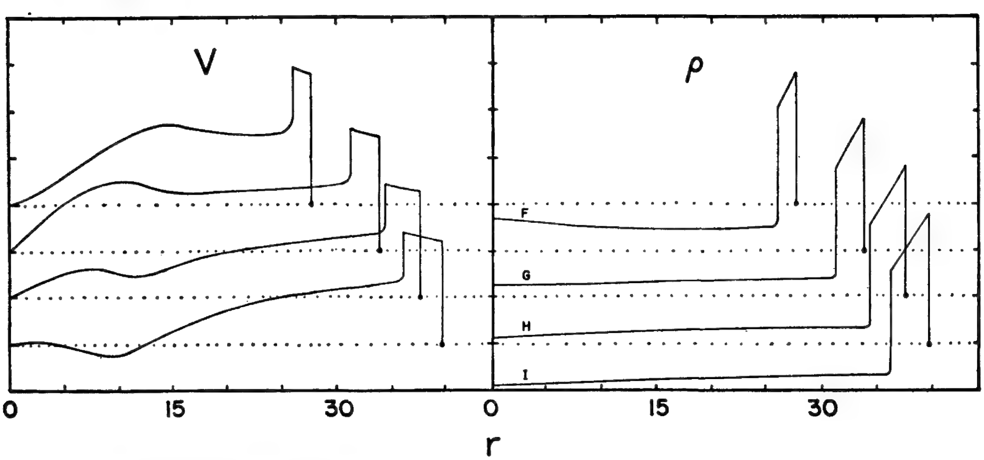


FIG. 12. Models F–I continue the sequence of nebulae with ages of 9×10^5, $1{\cdot}4 \times 10^6$, $1{\cdot}8 \times 10^6$ and 2×10^6 years, respectively. (Lasker 1966, reproduced from *The Astrophysical Journal*.)

7. THE DISTRIBUTION OF MASSES AMONG H I CLOUDS

The motion in the H I regions of space is known to be irregular, with random velocities of the order of 10 km/sec. In the *standard model* of the interstellar gas there are, on average, some ten clouds along a line of sight of 1 kpc length through the galactic disk. In this length the amount of material intercepted amounts to about 3×10^{21} H atoms per cm^2 column. The temperature of neutral-hydrogen gas appears to be about 100 or 125 °K, and the clouds fill about 10% of the volume available. For a detailed discussion of these observational data, see elsewhere in this volume (Van Woerden, Paper 1).

The model is contradicted by the observation, at 21 cm wavelength, of deep and sharp absorption lines against the background continuum of distant radio sources. The absorption profile due to a standard cloud would be neither as sharp, nor as deep. There are also philosophical difficulties in using the model. An interstellar cloud so defined is not gravitationally bound, and would simply expand. There is no evidence that any low-density, high-temperature medium exists in the space between the clouds to keep them in equilibrium. It is therefore not to be expected that clouds will continue to exist as well-defined units. The most reasonable statement seems to be that *the term 'cloud' is a simple expression to describe a region of high density with a small velocity gradient.* Many such regions must form in the interstellar gas in its state of supersonic agitation. Of course one cannot clearly define where a cloud begins and where it ends, but the concept of a cloud has as much validity as the concept of an eddy has in the study of incompressible turbulence. Even if both represent a great oversimplification, they can still be usefully employed.

Field and Saslaw (1965) have pushed the cloud concept to one of its limits. They study the properties of a *hypothetical population of clouds, each formed by the merging of smaller clouds.* The basic cloud has a mass of $30\,M_\odot$. They suppose it to have been formed on the outside of an expanding H II region, which in turn develops near a newly-formed O star that has been born in a collapsed cloud of large mass.

The probability for the amalgamation of two clouds is taken to be independent of their mass: thus, Field and Saslaw make no allowance for possible relations between a cloud's mass and its cross-section, or between its mass and its speed. They expect a cloud to become gravitationally unstable and to be removed from the system when its mass exceeds m_1 basic masses; in the present case $m_1 = 1300$. *A fraction* $1 - \eta$ *of a collapsed cloud then forms into stars*; the remainder stays interstellar, is accelerated outwards following the heating due to the newly formed stars, and returns to space in the form of unit clouds, with renewed kinetic energy.

A distribution function can be found for the clouds, with the form

$$N(m, t) = A(t)\, p(m). \tag{15}$$

$A(t)$ describes the temporal variation of the number of interstellar clouds and has the form

$$A(t) = \frac{A(0)}{1 + \alpha a A(0) t}\ ; \tag{16}$$

α and a in this formula are constants used in the calculation. $A(t)$ tends ultimately to vary inversely with the time t. *The net rate of loss of interstellar material varies as the square of its total mass.* In the present model, Field and Saslaw equate this rate to the rate

of star formation; in a more realistic model one would make allowance for the return of matter from evolved stars into space. But the general result tallies with an empirical model, due to Schmidt (1959), in which the rate of star formation per unit volume depends on the square of the density of the interstellar gas. This follows from the assumption that the amalgamation into massive clouds is due to a binary-collision process.

Field and Saslaw deduce numerical values for various parameters. In particular they show that the probability of finding a cloud of mass m should vary like $m^{-3/2}$, in the intermediate mass range. The *predicted mass spectrum* diverges from this simple power law for small clouds, and for clouds approaching the maximum size.

Some critics may hold that this result cannot be applied to the real interstellar gas, since the concept of a cloud arises from an oversimplification of the facts. But the general conclusion drawn from the work must surely stand, and must also follow from other theoretical models of the process of cloud amalgamation. Within a time of the order of 10^8 years only, most of the interstellar matter must collect into massive complexes, which will be gravitationally unstable. In fact, though, observation shows that the interstellar gas condenses into stars at a much slower net rate. In any one complex only a small fraction $1 - \eta$ should therefore form stars. According to Field and Saslaw, $1 - \eta = 0{\cdot}03$.

8. THE ENERGY BALANCE OF H I REGIONS

Three types of physical process are involved in the energy balance of H I regions. They are:

(*i*) the communication of organized energy to the interstellar gas by expanding H II regions and/or expanding supernova remnants;

(*ii*) the degradation into thermal energy of the kinetic energy of the mass motion of interstellar clouds;

(*iii*) the radiative processes which cause the clouds to lose thermal energy, and the balance between them and the processes which heat the gas.

Let us first consider the *thermal balance of the clouds*. It is generally agreed that the gas clouds cool by the collisional excitation of some of their minor constituents, such as H_2, C^+, Si^+, and so on, and their subsequent de-excitation by radiation. The excitation occurs more readily at higher temperatures. It seems likely that clouds gain most of their heat during occasional collisions with other clouds. After a collision a cloud is hot, and will cool fast. Later the cloud spends most of its time at a rather low temperature, cooling slowly. Mean values of cloud temperatures are therefore most strongly affected by the typical time lapse between cloud collisions. If collisions occur more frequently, there will be no time for the typical cloud to cool to a very low temperature. On the other hand, if collisions are more violent and release more heat, then the clouds will be somewhat hotter for a very short time, but the change will hardly affect the temperatures observed. This conclusion applies particularly in the case where the temperature is inferred from measurements of the optical depth of interstellar hydrogen at 21 cm wavelength. A given mass of hydrogen contributes to such measurements with a weight inversely proportional to its temperature. A cool cloud therefore shows up well, a warm cloud hardly at all.

The temperatures in neutral hydrogen clouds turn out to be somewhat higher than

one would expect from calculations of their thermal balance (cf. Kahn and Dyson 1965). The discrepancy cannot easily be removed by assuming that cloud-cloud collisions are more violent, but it would be relaxed if they occurred more frequently.

It is easy to estimate the *rate at which the kinetic energy of gas clouds degrades into heat*, according to the standard model of the interstellar gas. An arbitrary line, drawn through interstellar space within the galactic disk, will on average cut one cloud in every 100 pc ($\equiv l$). The typical cloud has a speed of 10 km/sec ($\equiv v$), and is involved in a collision once in a period $l/v\sqrt{2}$, on average. The factor $\sqrt{2}$ occurs because both partners in a collision will be in motion. The collision degrades the kinetic energy contributed by one degree of freedom, or $v^2/6$ per unit mass. The rate of loss of organized energy becomes $v^3/3l\sqrt{2} \approx 8 \times 10^{-4}$ erg g^{-1} s^{-1}. This value will be reduced if the collisions are partly elastic, for example if the magnetic field H pervading the interstellar gas is strong enough for the Alfvén speed to exceed 10 km/sec, the typical cloud speed. This requires that $H > 5 \times 10^{-6}$ gauss. Alternatively, the relative velocities in a typical cloud-cloud encounter would tend to be lower if there were a correlation between velocities in neighbouring clouds. There is at present no evidence that either of these provisos applies.

Finally one can estimate *how much kinetic energy the* H I *regions will gain from expanding* H II *regions*. The method is based on an argument due to Biermann (1962). There are some 6×10^{40} g of interstellar matter in a volume of 10^9 pc^3 of the galactic disk in the vicinity of the Sun. The stars of spectral types O-B1 contained in the volume have a total luminosity of about 8×10^{40} erg/s. Stars of later spectral type do not have large enough H II regions, and contribute negligibly to the energy input.

Now, as was discussed in Section 6, Lasker has found that some 10^{49} erg of kinetic energy is given by an O7 star to its H II region and to the surrounding H I shell; this value is appropriate in the case where the medium surrounding the star had an initial density $n_0 = 6{\cdot}4$ atoms/cm^3. We now assume that an O7 star has a mass of 30 $M_\odot$, and that it consumes one-third of its hydrogen before it has moved so far off the main sequence that it can no longer maintain its H II region. During this phase it emits some 10^{53} erg, of which one part in 10^4 is converted into kinetic energy of the interstellar gas. It seems reasonable to take an O7 star as representative of the class of stars which excite H II regions, and to adopt the same efficiency factor 10^{-4} for all these stars. If so, the early-type stars in the chosen region communicate energy at the rate of 8×10^{36} erg/s to the 6×10^{40} g of interstellar matter there. This rate of input is about $1{\cdot}4 \times 10^{-4}$ erg g^{-1} s^{-1}, smaller than the estimated rate of dissipation by a factor of about 6. In view of the uncertain nature of the data this does not prove conclusively that H II regions contribute an insufficient amount of energy; on the other hand it certainly cannot be established by an argument like this that the energy input from H II regions is by itself sufficient to maintain the motions of the H I clouds.

Estimates of the kinetic energy released in H II regions depend on the assumed value of n_0. The volume of the H II region around the star varies, at later stages, like n_0^{-2}, and so the mass and the energy contained in the region vary like n_0^{-1}. Thus, if $n_0 = 1$ atom/cm^3 around the typical early-type star, just after formation, then the predicted rate of energy input matches the rate of energy dissipation. But this is a very low value for n_0. In fact, the detailed discussion of the Orion Nebula, for example, seems to show that much of the atomic hydrogen, before ionization, is collected in condensations which have rather a high density. Cooling processes will be more important there, and smaller amounts of organized kinetic energy will be released.

In view of these uncertainties, Kahn and Woltjer (1967) have tried to revive the *hypothesis that supernova remnants supply most of the kinetic energy* of the H I regions. They describe their calculation in a short communication to this Symposium (Paper 16). Given some optimism one can claim that supernovae do provide the required energy. One interesting consequence of the hypothesis is that at all times a very large proportion of the interstellar clouds actually form part of expanding shells around old supernovae. This should introduce into the motions in interstellar space a degree of regularity which might well be detectable.

Acknowledgments

The author thanks Dr J. E. Dyson and Mr D. A. Mendis for allowing him to quote some of their unpublished results. He is also grateful to Drs L. Biermann, G. Herzberg and L. Spitzer for their helpful comments.

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REFERENCES

Abramowitz, M., Stegun, I. A. 1965, *Handbook of Mathematical Functions*, Dover Publ., New York, p. 319.

Axford, W. I. 1961, *Phil. Trans. R. Soc. Lond. A*, **253**, 301.

Biermann, L. 1962, in *Interstellar Matter in Galaxies*, Ed. L. Woltjer, W. A. Benjamin, New York, p. 153.

Dyson, J. E. 1966, *The Age and Dynamics of the Orion Nebula*, Thesis, Manchester.

Field, G. B., Saslaw, W. C. 1965, *Astrophys. J.*, **142**, 568.

Goldsworthy, F. A. 1961, *Phil. Trans. R. Soc. Lond. A*, **253**, 277.

Hjellming, R. M. 1966, *Astrophys. J.*, **143**, 420.

Kahn, F. D., Dyson, J. E. 1965, *A. Rev. Astr. Astrophys.*, **3**, 47.

Kahn, F. D., Woltjer, L. 1967, IAU Symposium, no. 31, *Radio Astronomy and the Galactic System*, Ed. H. van Woerden, Academic Press, London (Paper 16).

Lasker, B. M. 1966, *Astrophys. J.*, **143**, 700.

Mathews, W. G. 1965, *Astrophys. J.*, **142**, 1120.

Mendis, D. A. 1967, Structure and Propagation of Dissociation—Ionization Fronts in Interstellar Gas Clouds, Thesis, Manchester.

Menon, T. K. 1961, *Publ. nat. Radio Astr. Obs.*, **1**, 1.

Schmidt, M. 1959, *Astrophys. J.*, **129**, 243.

Vandervoort, P. O. 1963, *Astrophys. J.*, **139**, 869.

Wilson, O. C., Münch, G., Flather, E. M., Coffeen, M. F. 1959, *Astrophys. J. Suppl. Ser.*, **4**, 199.

I.A.U. Symposium no. 31, 1967

16. SUPERNOVAE AND INTERSTELLAR GAS DYNAMICS

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ABSTRACT

The efficiency of the transfer of energy from supernovae into interstellar cloud motions is investigated. A lower limit of about 0·002 is obtained, but values near 0·01 are more likely. Taking all uncertainties in the theory and observations into account, the energy per supernova, in the form of relativistic particles or high-velocity matter, needed to maintain the random motions in the interstellar gas is estimated as $10^{51\cdot 4 \pm 1}$ ergs.

1. CONVERSION OF SUPERNOVA ENERGY INTO ENERGY OF CLOUD MOTIONS

Consider a supernova in a typical H I region. A large fraction of its energy will ultimately be lost radiatively. A small fraction may be converted into kinetic energy of the interstellar gas. To calculate this fraction we adopt two alternative models.

a. In the first model *relativistic particles with a total energy* E_* are released at the time of the explosion ($t = 0$) within a small volume, which is surrounded by a uniform quiescent cold gas of density ρ_0. At a later time the relativistic particles will have a total energy E and will fill a sphere of radius R. Since the ratio γ of specific heats equals 4/3 for a relativistic gas, it follows that $E \propto R^{-1}$, and we therefore write $E = E_* R_*/R$, where R_* is a typical length which we shall define later. The sphere will be surrounded by a shell of gas which has been swept up. If radiative losses are sufficiently large, the shell will be thin and its mass equal to $(4\pi/3)\,\rho_0 R^3$. Since we neglect the thickness of the shell, we obtain for its equation of motion

$$\tfrac{1}{3}\rho_0\, R^3 \frac{d^2R}{dt^2} + \rho_0 R^2 \left(\frac{dR}{dt}\right)^2 = \frac{E_* R_*}{4\pi\, R^2} \quad . \tag{1}$$

The first term in this equation represents the mass per unit solid angle of the shell, multiplied by the acceleration. The second gives the rate of change of momentum, per unit solid angle per unit time, of the matter swept into the shell. The term on the right-hand side equals the force per unit solid angle due to the relativistic gas, PR^2, where the pressure P of the gas equals one-third of its energy density. Equation (1) can easily be integrated to give

$$\left(\frac{dR}{dt}\right)^2 = \frac{3}{4\pi}\,\frac{E_* R_*}{\rho_0\, R^4} + \frac{A}{R^6} \quad , \tag{2}$$

with A a constant of integration. We shall be interested in the solution for large values of R, for which the second term on the right-hand side becomes negligible. Since we have treated the interstellar gas as pressure-free, equation (2) should not be used when dR/dt becomes equal to the velocity dispersion in the interstellar gas.

To find a minimum value for R_* we must consider the early phases of the expansion. Initially the energy density of the relativistic gas is so high that the interstellar gas can offer no effective resistance, and the relativistic gas expands almost as in a vacuum, without change of energy. The adiabatic relation between energy and volume becomes valid only when the relativistic particles begin to have a velocity distribution which is reasonably isotropic. This requires that each relativistic particle should transfer to the shell an amount of momentum of the order of its own initial momentum, and that the shell move with a velocity rather less than the velocity of light. The mass of the shell must therefore be at least E_*/c^2, and its radius at least $[3E_*/(4\pi\rho_0 c^2)]^{1/3}$. At this stage the energy of the relativistic gas is still approximately E_*, and so R_* certainly cannot be less than this minimum radius. If R_* is taken equal to it, we find from equation (2) for the late stages of the motion that

$$\frac{dR}{dt} = \left(\frac{3E_*}{4\pi\rho_0 c^{1/2}}\right)^{2/3} \frac{1}{R^2} \quad . \tag{3}$$

To reproduce the motions in the interstellar gas, we have to give each element of gas a velocity V_0 about equal to a typical interstellar-cloud velocity of 10 km/sec. To obtain the total mass M of the gas accelerated to this velocity, we take R from equation (3) with dR/dt replaced by V_0. We then find for the total kinetic energy of this gas

$$\tfrac{1}{2}MV_0^2 = \tfrac{1}{2}E_*\left(\frac{V_0}{c}\right)^{1/2} \quad . \tag{4}$$

If R_* is larger than the minimum value, MV_0^2 is increased proportionally.

b. As an alternative model we consider that the energy E_* emerges not in the form of relativistic particles, but as *kinetic energy of a mass M_* ejected with velocity V_**. In our snow-plough approximation the conservation of momentum in any solid angle then requires that $M_*V_* = MV$ at any later time. Hence the total kinetic energy at the time when the shell has velocity V_0 is given by

$$\tfrac{1}{2}MV_0^2 = \tfrac{1}{2}M_*V_*V_0 = \frac{V_0}{V_*}E_* \quad . \tag{5}$$

Taking as a typical value $V_* = 7000$ km/sec, we find with $V_0 = 10$ km/sec that the *fraction of the energy input that can be communicated to the interstellar gas* is 0·003 for the first model and about half as large for the second model. We stress again that these are probably lower limits. First of all we have taken, for R_*, the smallest possible value in a uniform interstellar medium. Both because R_* depends sensitively on the magnetic-field structure and because the intercloud distance in typical interstellar regions is near 10 pc (while the minimum R_* for a uniform medium will turn out to be somewhat less than 1 pc), the actual efficiency factor should be higher for the relativistic-particle case. Furthermore, the radiation probably will not be sufficient to keep the matter cool in the early phases, when, in our solutions, most of the energy is dissipated. Thus a region of high pressure will build up around the expanding matter, and this again will considerably

raise the efficiency of the final conversion into 'useful' kinetic energy of the interstellar gas. We feel therefore that equations (4) and (5) may yield efficiency factors that are too low by a full order of magnitude.

2. DISSIPATION OF ORGANIZED ENERGY IN INTERSTELLAR SPACE

We shall now estimate how much energy is needed to maintain the random motions of interstellar gas clouds. Simple theory leads to a dissipation rate of $V_0^3/3l\sqrt{2}$ per unit mass per unit time, l being the mean free path for an interstellar gas cloud. Observations of interstellar absorption lines (cf. Paper 1) indicate that l is approximately 100 pc. With $V_0 = 10$ km/sec, the dissipation rate becomes 8×10^{-4} erg g^{-1} sec^{-1}. The current estimate for the total mass of interstellar gas in the Galaxy is $M = 5 \times 10^9 \odot \equiv 10^{43}$ g. In all, the interstellar gas therefore dissipates energy at the rate of 8×10^{39} erg/sec. If supernovae supply this energy, and if we assume an efficiency factor of 0·01, then they must inject energy at a rate of 8×10^{41} erg/sec for the Galaxy as a whole. If the supernova rate is one event per 100 years, then the energy E_* released in a typical supernova must be of order $2{\cdot}5 \times 10^{51}$ erg. Most of the supernova energy is dissipated in the form of radiation, and it is worth noting that the total rate of dissipation would amount to a few per cent of the luminosity of a typical galaxy. The available observations of supernova remnants neither support nor contradict the value of E_* deduced. The numbers we have used for V_0, l and M are uncertain, and may be wrong by factors 1·2, 2·0 and 1·6, respectively. There results in the total dissipation rate, $MV_0^3/3l\sqrt{2}$, an uncertainty of a factor 3, approximately. The rate of occurrence of supernovae is uncertain by the same factor. Consequently, our estimate of log E_* is uncertain by a standard error of log 4. This does not include the uncertainty of the efficiency factor, which is of the same order of magnitude.

3. A MODEL OF CLOUD MOTIONS

From the results in the previous sections, we find that the radius of a supernova shell is about 50 pc at the time when the velocity has dropped to 10 km/sec. Integration of the equation of motion shows that this radius is reached after about 2×10^6 years. The radius of the shell at this time is about 1/200 of the radius of the galactic disk, while its diameter is not much less than the thickness of the disk. There is a probability of the order of 10% that a supernova has occurred inside this volume in the time available. This model therefore implies that many interstellar gas clouds can be considered as parts of some old supernova shell.

We note from equation (2) that, during the late evolution when the A/R^6 term is negligible, the cosmic-ray energy in the shell is twice the kinetic energy of the shell. On our model, this would be expected to hold approximately for all interstellar space, if the cosmic rays can escape when the shell reaches its maximum extent. This seems plausible because parts of the shell will tend to emerge from the galactic gas layer at that stage.

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17. THE RADIAL VELOCITY OF THE ORION NEBULA FROM RADIO OBSERVATIONS

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ABSTRACT

Recent radio measurements in the 109α line, together with earlier optical data, indicate that the Orion Nebula moves away from the Orion Nebula Cluster, towards the observer, at 8 km/sec. The paper discusses briefly the associated problems of the time scale, the origin, and the energy source of the nebula.

Recently Mezger and Höglund (1967) have determined the radial velocity of the Orion Nebula by means of the hydrogen recombination line 109α emitted by the nebula. They measured the velocities of the center and of four points situated 3′ (arc), i.e. half the half-power beamwidth, north, south, west, and east of the center. The results are respectively $-2{\cdot}0 \pm 1{\cdot}2$ km/sec, $-2{\cdot}6 \pm 2{\cdot}4$ km/sec, $-7{\cdot}0 \pm 2{\cdot}5$ km/sec, $-9{\cdot}5 \pm 3{\cdot}1$ km/sec, and $-2{\cdot}4 \pm 2{\cdot}4$ km/sec, with reference to the local standard of rest. The velocity of the center of the nebula is in close agreement with the optical determination by Flynn (1965), who gives a value of $+1{\cdot}3 \pm 0{\cdot}8$ km/sec.

The radial velocities of a number of stars in the Orion Nebula Cluster have been measured by H. M. Johnson (1965), who confirms a *difference between the stellar and nebular velocities* of about 8 km/sec, with the nebula moving away from the cluster towards the observer. The usual interpretation of this difference has been (see Wilson *et al.* 1959) that the nebula is expanding with respect to the stars, and that the optical measurements of the nebula refer to the nearer, approaching side of the nebula, the farther side being obscured by extinction. However, the optical depth of the nebula at the center of the radio recombination line is extremely small, and hence the radial velocity measured in the radio line can be considered as that of the center of the mass present in the beam. In combination with the fact that the nebular helium lines, which are seen in absorption in the spectra of cluster stars, also show a velocity similar to the radio values, this suggests that *the center of mass of the nebula is in front of the stars.* This confirms the conclusion of Flynn (1965) from his optical measurements.

This interpretation of the distribution of gas and stars raises a number of interesting questions. The first concerns the *time scale of the system.* The radius of the nebula is about 1 pc, and that of the full cluster is about the same. With a velocity of 8 km/sec the ionized cloud will take about 10^5 years to leave the cluster, on the assumption of uniform motion; in the case of acceleration throughout the motion, the time scale could be substantially longer. The close correspondence in position of the centers of the nebula and the cluster suggests that the physical separation between the two may be less than the radius of the cluster. If this is true, then the time scale since the motion of the cloud started may be significantly shorter than the value derived above.

*The National Radio Astronomy Observatory is operated by Associated Universities, Inc., under contract with the National Science Foundation, Washington, D.C., U.S.A.

The second question concerns the *origin of the ionized cloud.* Is it related to the origin of the cluster or is the association with the cluster accidental? The close coincidence in position of the cloud and the cluster would seem to preclude the hypothesis of accidental association, particularly since the Orion Nebula has been shown to be an isolated high-density cloud.

The third question concerns the *energy source for the acceleration of the nebula.* One possibility to be considered is that the cloud is accelerated by the *radiation of the* O *star*, according to the process suggested by Oort and Spitzer (1955). There are a number of difficulties in the application of this mechanism to the case of the Orion Nebula. As discussed by Oort and Spitzer and by many others, the initial boundary of the Strömgren sphere will be established essentially instantaneously after the birth of an O star. It can be shown (see Menon 1962) that in the case of the Orion Nebula the initial boundary will include most of the Nebula. Since acceleration by the Oort-Spitzer mechanism strictly applies only to a neutral-hydrogen cloud, the acceleration in this case, then, must have been completed in the first few hundred years after the birth of the exciting star, before the cloud was completely ionized. If we apply the considerations of Oort and Spitzer, in their analysis of the effect of an O star on an isolated cloud, we find that in our case the acceleration falls short of the requirement by several orders of magnitude. However, uncertainties in the assumptions underlying the Oort-Spitzer theory are such that the O star cannot be ruled out at present as the cause of the acceleration of the cloud. Since the mass of the nebula is about 100 $M_{\odot}$, i.e. not much more than that of an O star, it is quite likely that at an earlier stage—before ionization—it was in a much more condensed form, and more directly related to the formation processes of the early-type members of the cluster. The kinetic energy of the ionized cloud at present is about 10^{47} erg. The radiant energy, beyond the Lyman limit, available from an O6 star is about 2×10^{38} erg/sec. Of this, only a fraction proportional to the solid angle at the star subtended by the cloud is incident on the cloud. Assuming a time scale, for ionization, of 500 years, we see that less than 2×10^{48} erg from the star is available for conversion. We do not at present know the *efficiency of conversion* of radiant energy into systematic motion of the nebula. However, if the Oort-Spitzer mechanism is responsible for the acceleration of the Orion Nebula, the above numbers indicate a high efficiency for the process.

There is one further comment I wish to make with regard to the velocity measurements. It concerns the apparent increase in radial velocity south and west of the center. This increase confirms a general result of Courtès (1960) from his optical studies. Some of the theories of expansion of H II regions predict such an increase of velocity with radius. Observations of the radial velocities with higher angular resolution will provide extremely interesting data bearing on the dynamics of ionized clouds.

REFERENCES

Courtès, G. 1960, *Ann. Astrophys.*, **23**, 115.
Flynn, F. H. 1965, *Mon. Not. R. astr. Soc.*, **130**, 9.
Johnson, H. M. 1965, *Astrophys. J.*, **142**, 964.
Menon, T. K. 1962, *Astrophys. J.*, **136**, 95.
Mezger, P. G., Höglund, B. 1967, *Astrophys. J.*, **147**, 490.
Oort, J. H., Spitzer, L. 1955, *Astrophys. J.*, **121**, 6.
Wilson, O. C., Münch, G., Flather, E. M., Coffeen, M. F. 1959, *Astrophys. J. Suppl. Ser.*, **4**, 199 (no. 40).

Discussion

F. D. Kahn: Could it be that the ionized material is streaming off the non-ionized material, and that the latter is on the far side of the cluster, while the ionized gas is coming towards us?

T. K. Menon: How could you have much non-ionized material, when there are so many O and B stars behind the cluster, and the interstellar absorption lines also show the velocity of the ionized gas? There is no indication in the 21-cm radiation either that there is any higher density behind the cluster.

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18. THE ENERGIZATION OF THE INTERSTELLAR MEDIUM BY IONIZATION-LIMITED H II REGIONS

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ABSTRACT

The energy input into the interstellar medium from ionization-limited H II regions is estimated at $1 \cdot 4 \times 10^{-28}$ erg cm^{-3} sec^{-1}, an order of magnitude lower than the anticipated dissipation.

As suggested several years ago by Oort and Spitzer (1955) and as previously discussed in this session by Kahn (Paper 15), the expansion of H II regions may furnish significant kinetic energy to the interstellar gas. Some recent results concerning the efficiency of this process in the case of ionization-limited H II regions are of interest. Detailed models of the dynamics of such H II regions by Mathews (1965) and by Lasker (1966) suggest that the mean energy per Lyman-continuum photon which actually goes into the kinetic energy of expansion is small—about 0·08 eV/photon for my model for a two-million year old nebula with an initially homogeneous density of 6 cm^{-3} and excited by an O7 star.

I shall now outline a simple heuristic model for the dynamics of old H II regions, which is based on results of the previously available detailed calculations (Vandervoort 1963, 1964; Mathews 1965; Lasker 1966), and which gives a satisfactory approximation for the kinetic energy in the accelerated H I shell. The formation phases, occurring in a time short compared to the lifetime of the exciting star, are characterized by little expansion. Accordingly a suitable approximation to the dynamics is that the expansion begins from a just-formed H II region and continues for the lifetime of the exciting star. The expanding H II region may be considered as a piston which accelerates an H I shell by driving a strong shock into the neutral gas. Reference to the detailed dynamical models and to the properties of Rankine-Hugoniot shocks indicates that the velocities of the ionization front and of the shock at the time of formation are approximately equal to the sound speed in the H II region, and vary roughly as the square root of the mean gas pressure in the H II region. Then it is easy to calculate the locus of the ionization front and the work done by the expanding H II region.

Half of this work goes into heating by the adiabatic shock and is eventually radiated away; the remainder goes into the kinetic energy of the expanding H I shell. Next, knowing the available excess ultraviolet flux from the exciting star (see Spitzer 1967), it is straightforward to calculate the mean efficiency for transferring energy from the Lyman continuum into kinetic energy in an expanding H I shell. The following table gives some numerical results for stars of various spectral types exciting nebulae with initially homogeneous densities of 10 cm^{-3}:

Spectral Type	O5	O6	O7	O8	O9	B0	B1
Efficiency	·0019	·0035	·0062	·011	·020	·036	·069

These efficiencies are low; obviously most of the energy of the exciting star goes into maintaining the temperature and ionization of the H II region, and little goes into the kinetic energy of the expanding H I shell.

According to Spitzer's (1967) discussion, the energy dissipation from collisions between neutral-hydrogen clouds is roughly 10^{-27} erg cm^{-3} sec^{-1}, depending somewhat on the magnetic-field strength. In his (totally efficient) low-density limit Spitzer finds about 6×10^{-26} erg cm^{-3} sec^{-1} to be available from expanding H II regions, while the present results imply about $1{\cdot}4 \times 10^{-28}$ erg cm^{-3} sec^{-1}, a value somewhat less than the anticipated dissipation.

This result would imply that the energy input from H II regions is insufficient to balance the dissipation, if H II regions were ionization-limited. Surely not all H II regions are ionization-limited, and the true situation probably lies somewhere between the present model and Spitzer's low-density limit. Further work to determine what really are the ionization and excitation conditions in a representative sample of H II regions, and how efficiency varies with the geometry of the regions, is needed.

The details of this work are to be reported elsewhere (Lasker 1967). The author is supported by a National Science Foundation Postdoctoral Fellowship.

REFERENCES

Lasker, B. M. 1966, *Astrophys. J.*, **143**, 700.
Lasker, B. M. 1967, *Astrophys. J.*, in press.
Mathews, W. G. 1965, *Astrophys. J.*, **142**, 1120.
Oort, J. H., Spitzer, L. 1955, *Astrophys. J.*, **121**, 6.
Spitzer, L. 1967, Dynamics of Interstellar Matter and the Formation of Stars, in *Nebulae and Interstellar Matter*, Eds. L. H. Aller and B. M. Middlehurst, Vol. VII in the series: *Stars and Stellar Systems*, Univ. of Chicago Press, Chicago, chapter 9, in press.
Vandervoort, P. O. 1963, *Astrophys. J.*, **138**, 426.
Vandervoort, P. O. 1964, *Astrophys. J.*, **139**, 889.

19. A POSSIBLE SUPERNOVA REMNANT OBSERVED IN 21-CM EMISSION

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In the course of one of the investigations listed in Paper 29, we have studied a disturbance in the observed neutral-hydrogen distribution in the galactic plane. The figures derived for this feature show excellent agreement with those quoted by Kahn and Woltjer (Paper 16) as the expected result of a supernova explosion. The results of a preliminary discussion are given in the following table.

$l^{\mathrm{II}}, b^{\mathrm{II}}$	$61\overset{\circ}{.}6, -0\overset{\circ}{.}6$
distance	5 kpc
radius	125 pc
mass of neutral hydrogen	$2 \times 10^4 M_\odot$
expansion velocity	8 km/sec
kinetic energy	2×10^{49} erg
age	5×10^6 years

The hydrogen mass derived from this preliminary investigation is subject to an uncertainty of at least a factor two.

There is no known radio-continuum source or optical object associated with this disturbance; therefore any identification of it as the result of a supernova explosion must remain highly speculative.

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20. THE EFFECT OF MAGNETIC FIELDS ON INTERSTELLAR CLOUDS

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I should like to say something about the equilibrium of the gas in spiral arms and about the interaction of interstellar clouds. The polarization of the light of distant stars shows that there is a quasi-regular magnetic field inside the clouds, and the Faraday rotation indicates the same for the gas between the clouds.

According to Chandrasekhar and Fermi (1953), the magnetic field may be responsible for the stability of the spiral arms. They have considered the case of a smooth density distribution, but if we also take the cloudy structure of the interstellar medium into account, we find an equilibrium configuration like that in Figure 1. The magnetic lines of force are deformed and support the cloud against gravitation. For an ordinary cloud, the depth of the well is only a few parsecs, and the cloud can disperse along the lines of force. If, on the other hand, the density is 5 to 10 times greater, the gas will tend to concentrate; the well will deepen and other, heavy complexes of gas, moving along the magnetic lines, will fall in.

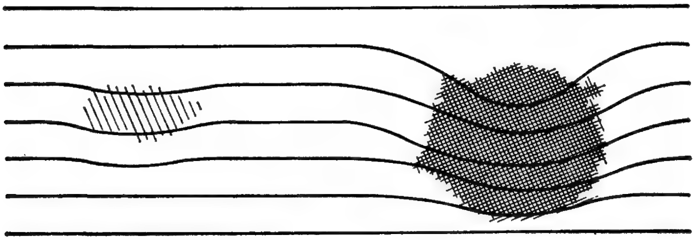

Fig. 1. Interstellar clouds supported against gravitation by a magnetic field.

When the mass and the density of such a complex get rather large, stars may be formed in it, and H II regions and supernovae appear. The cold gas is pushed away and divided into clouds, as in the famous theory of Oort and Spitzer (1955), which has recently been further developed by Field and Saslaw (1965). These clouds will penetrate into the magnetic field of the arms, where they will be divided by interchange instability into thin filaments parallel to the magnetic lines. In a short time, the field lines will penetrate into the thin filaments by ambipolar diffusion; then the ions and charged dust particles in the filaments become bound to the field lines, so that the filamentary structure is also fixed to the field. Slowly the neutral atoms diffuse relative to the charged particles, and after some time will be smoothly distributed while the dust is still in filaments. This explains the filamentary structure of some reflection nebulae. In several million years the filaments will disappear owing to gravitational drift.

The movements of such clouds perpendicular to the magnetic field form some sort of oscillation, which we observe as random velocities. The velocity amplitude of such oscillations depends on the mechanism responsible for motions in the spiral arms. These motions will dissipate slowly if the collisions of the interstellar clouds are elastic. There is a general field of random motions and the clouds exchange their energy through various kinds of waves.

REFERENCES

Chandrasekhar, S., Fermi, E. 1953, *Astrophys. J.*, **118**, 113 and 116.
Field, G. B., Saslaw, W. C. 1965, *Astrophys. J.*, **142**, 568.
Oort, J. H., Spitzer, L. 1955, *Astrophys. J.*, **121**, 6.

I.A.U. Symposium no. 31, 1967

21. ON PETSCHEK'S MECHANISM FOR DISSIPATING INTERSTELLAR MAGNETIC FIELDS

DONAT G. WENTZEL

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ABSTRACT

Petschek's solution for the hydromagnetic flow at a magnetic neutral plane is applied to the interior of interstellar clouds. The stationary flow between the opposed magnetic fields involves a streaming speed of about 3 km/s and a gas density of roughly 10^2 atoms/cm^3. At most one-tenth of all the gas resides in these streams, but their low temperatures should make them observable in absorption at 21 cm; they may even dominate the interstellar absorption lines of Ca^+ and of Na, since the abundance of these absorbing ions, proportional to the recombination rate of the dominant ions with electrons, depends on the square of the gas density. Optical and 21-cm lines may, therefore, represent somewhat different samples of the interstellar velocity and density distributions.

In analogy to the geomagnetic field, which is separated from the interplanetary field, interstellar clouds may be separated from the general galactic magnetic field. Such magnetic bubbles can move through the galactic field without twisting it, but they can maintain their identity only if they contain a twisted magnetic field. This field leads to the operation of Petschek's Mechanism and makes these clouds prominent in the optical absorption lines. A full evaluation of Petschek's Mechanism must involve some plasma instability to reconnect the lines of force.

Details of this work have appeared elsewhere (Wentzel 1966).

REFERENCE

Wentzel, D. G. 1966, *Astrophys. J.*, **145**, 595.

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I.A.U. Symposium no. 31, 1967

22. DIRECT TRANSFORMATION OF MAGNETIC-FIELD ENERGY INTO ENERGY OF FAST PARTICLES

S. I. Syrovatskii

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There are two distinct but as it seems strongly connected problems. The first is the surprisingly rapid dissipation of magnetic fields which is observed in the Sun's atmosphere and must be supposed for some other objects as well. The second problem is the acceleration of fast particles in magnetized cosmical plasma.

The idea which I am going to discuss is in some respects analogous to that in papers published by Sweet, Dungey, Petschek, Chapman and Kendall and in the communication by Wentzel at this Symposium (Paper 21). Namely, we shall consider the magneto-hydrodynamic flow near the neutral line of a magnetic field. We may illustrate the situation by pictures of the field that can arise in a group of sunspots (Figure 1) or of a highly-disordered turbulent magnetic field with nearly-closed loops of field lines (Figure 2). For both cases, in the two-dimensional problem we have a neutral line. For the sake of simplicity, this line may be considered as the neutral line between two parallel currents (cf. Figure 3).

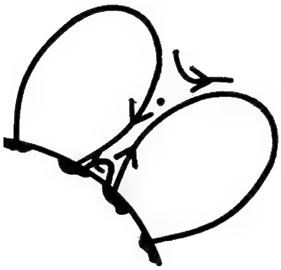

Fig. 1. Magnetic field of a group of sunspots.

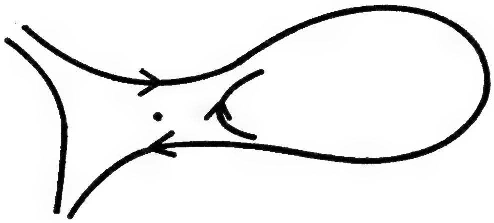

Fig. 2. Turbulent magnetic field with nearly-closed loops of field lines.

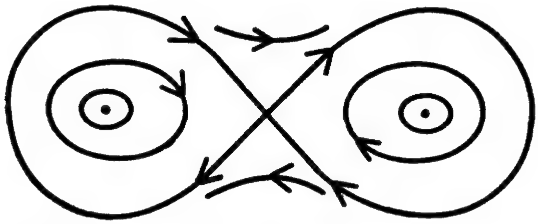

Fig. 3. Magnetic field of two parallel currents.

The question is: what kind of flow of plasma will arise if we change or move the currents? This is a quite difficult, non-linear mathematical problem of non-stationary two-dimensional magneto-hydrodynamic flow, but nevertheless it can be analyzed in some approximation. I shall here give only qualitative results.

At some distance from the neutral line, the solution has the property of a converging cylindrical wave, which leads to a cumulative effect with a strong increase of field gradients towards the neutral line. The essential point is the fact that the number density of the plasma grows much more slowly and in some regions may even decrease. It follows then that the ratio of electric current density, j, to number density of plasma, n, tends formally to infinity. But since $j < n e c$ (where c = velocity of light), the flow can continue only to this limit approximately, and there the magneto-hydrodynamical condition of a magnetic field 'frozen into' the plasma breaks down. The magnetic field changes into a free (inductive) electric field, which accelerates the charged particles of the plasma. Strictly speaking, under such conditions we have not a plasma, but individual particles in a strong, large-scale electric field. The result of this process is a dissipation of some part of the magnetic energy, which is converted into kinetic energy of the accelerated particles.

The general statement of this problem and some preliminary results have been published (Syrovatskii 1966*a*, 1966*b*).

REFERENCES

Syrovatskii, S. I. 1966*a*, *Astr. Zu.*, **43**, 340.
Syrovatskii, S. I. 1966*b*, *Soviet Phys. JETP*, **23**, 754.

I.A.U. Symposium no. 31, 1967

23. GENERAL DISCUSSION ON INTERSTELLAR CLOUDS*

S. A. Colgate: The Field and Saslaw (1965) spectrum of *cloud sizes* (Kahn, Paper 15, Section 7) has a cut-off at mass m_0. I suspect that a minimum-size discontinuity exists, due to a change in the hydrodynamics of subsonic collisions at Reynolds numbers around 100. For larger Reynolds numbers the shearing flow is turbulent, and eddies of gas would be separated off. If the Reynolds number is smaller, the flow is laminar, the friction is stronger and I should expect more coalescence of the clouds. Are such considerations applicable?

F. D. Kahn answers: At a rough estimate, the Reynolds number for motions of interstellar clouds is of the order of 10^5, much larger than the critical number you have in mind. Further I do not think that one can easily extend inferences from the study of subsonic turbulence and apply them to the supersonic motions in interstellar space.

G. L. Verschuur: I wish to comment on a possible relationship between the *globules* discussed by Kahn (Paper 15, Sections 3 and 4) and OH *emission sources* and their polarization characteristics. The globules appear to contain the hydrogen molecules and oxygen atoms that are necessary for the OH formation process described by Salpeter (Paper 8, Section 3). Further, the globules have the very small angular extent (in Kahn's example for the Orion Nebula: 1 or 2 seconds of arc) required by the observations of OH emission reported by Robinson (Paper 7, Section 8) and Burke (Paper 9). If one allows the OH emission to originate in the globules, it is interesting to consider what happens to the radiation as it leaves the H II region. Kahn mentioned that there might be regions, between two globules say, where shock fronts would collide. The electron densities would be very high indeed and magnetic field lines would be considerably compressed. Perhaps, in localized regions, conditions could become extreme enough to introduce circular polarization of radio-frequency radiation traversing the medium, in the same way that regions in the solar corona produce circular polarization of radio bursts by differential absorption; apart from the Zeeman effect, this is the only known way of producing circular polarization.

The Berkeley group has reported variations of the OH emission with time (cf. Paper 10). If these indicate variations occurring in the shock-front collision regions, one might also expect changes in the polarization characteristics of the escaping radiation, for instance in the rotation measures (which in any case probably are very high in the H II region) and hence in the plane of polarization observed. As noted by Robinson (Paper 7, Section 7), there is disagreement between two groups of observers as to the polarization of OH emission from NGC6334: one group observed circular polarization, another linear. If we allow conditions as extreme as those suggested above for production of circular polarization, we might not be surprised if changes in the medium were of such

*Part of this discussion was held after the talks of Dr Kahn (Papers 15 and 16) and Dr Pikel'ner (Paper 20); the remainder at the end of the session devoted to Chapter IC, or in the subsequent overall-discussion of Part I of the Symposium programme. Since the subject matter of these three discussion periods was strongly related, I have collected all these remarks under one heading, and in the process considerably rearranged them.—*Editor*.

a nature as to sometimes allow transmission of linearly polarized radiation and at other times to decouple the modes and allow only one mode of circular polarization to escape.

Mrs N. H. Dieter adds: The OH emission from the Orion Nebula may be a source of information on the model described by Kahn for globules within the nebula. The 18-cm line profiles observed in Orion are in several ways unusual—in shape, and in the fact that the emission comes from the centre of the nebula, not from the edge. The velocities of the major intensity peaks are separated by just the same amount as the optical lines, supporting the double-peaked line profile which is an outcome of Dyson's model.

*G. Herzberg**: In connection with Kahn's discussion (Paper 15, Section 5) of the possible reactions involving H_2^+ in the interstellar medium, I should like to call attention to the possible importance of the reaction of H_2^+ ions with neutral hydrogen molecules:

$$H_2^+ + H_2 \rightarrow H_3^+ + H.$$

From mass-spectrometric data, this is well known to be a very fast reaction, occurring at practically every collision. It appears likely that as a consequence of this reaction there is a small concentration of H_3^+ present in the interstellar medium. Theoretical calculations have shown that the dissociation energy of H_3^+ is about 3·7 eV. In other words, H_3^+ is a fairly stable system. It will, of course, be subject to photoionization and photodissociation. Up to now, in spite of considerable effort, no absorption spectrum of H_3^+ has been observed.

The presence of H_3^+ in the interstellar medium might give rise to the formation of CH^+ and OH^+ by the following reactions:

$$H_3^+ + C \rightarrow CH^+ + H_2 \quad \text{and} \quad H_3^+ + O \rightarrow OH^+ + H_2.$$

These reactions are expected to be exothermic. However, the reactions

$$H_3^+ + C \rightarrow CH + H_2^+ \quad \text{and} \quad H_3^+ + O \rightarrow OH + H_2^+$$

are endothermic and not likely to play a role.

Colgate: For the *conversion of supernova energy* into energy of cloud motions (Kahn and Woltjer, Paper 16), I would rather consider velocities of the order of 2×10^9 cm/sec for the supernova ejecta than the velocity of light.

Kahn answers: We tried out a model with relativistic particles to see how it would work, and it seemed to do quite well (Section 1*a* of Paper 16). But a model with larger initial energy and smaller speed (Section 1*b* of Paper 16) works just about as well.

M. P. Savedoff: The use of *relativistic particles* by Kahn and Woltjer (Paper 16) is unfortunate. We have observations of cosmic rays which are supposedly related to these relativistic particles. In particular, Ginzburg has called my attention to an estimate of cosmic-ray ages by Daniel and Durgaprasad (1966); from the ratio $^{10}Be/^{10}B$ they find that this age is greater than 5×10^7 years, or some ten times the supernova-shell age considered by Kahn and Woltjer. Thus, since the efficiency of using the relativistic energy is only 1/350, the total energy of relativistic particles stored in the Galaxy should be 3500 times that of the gas. This energy is probably sufficient for the relativistic particles to pull

*These remarks were made by Herzberg in private conversation with Kahn and a few other participants during the Symposium.—*Editor*.

all the gas from the Galaxy by the intervention of magnetic fields. The estimated cosmic-ray fluxes will also be too high, unless the cosmic rays extend to a volume exceeding 3500 times that of the gas, i.e. to a sphere of at least 40 kpc radius.

Kahn answers: In our model the initial energy of the relativistic particles is indeed some 350 times larger than the kinetic energy later given to the cool interstellar gas. But in the interim the relativistic particles do work in expanding the shell which encloses them, and we suppose that they are not released into space until the shell collides with another shell. By this time the typical shell velocity is about equal to the typical velocity of the interstellar gas, i.e., the shell has the kinetic energy to be expected of an equal mass of interstellar matter. One can readily show (cf. Paper 16, Section 3) that in the later stages of the motion the kinetic energy of the shell is of the same order as the energy of the relativistic particles. Thus our model agrees roughly with current ideas on the energy distribution in interstellar space.

L. Woltjer adds: It should be realized that, if relativistic particles from supernova ejecta are responsible for the acceleration of interstellar clouds, the cosmic-ray energy required is inversely proportional to the radius of the region into which the particles are originally injected. The figure of 3×10^{52} erg mentioned by Kahn in his talk corresponds to the absolute minimum radius of this region, and could easily be reduced by more than an order of magnitude. In our paper (Paper 16) we consequently give $2{\cdot}5 \times 10^{51}$ erg as a more realistic estimate. If high-velocity matter is injected instead of relativistic particles, the energy needed may be 10^{52} to 10^{53} erg.

V. L. Ginzburg asks: What is the *minimum* cosmic-ray energy per supernova needed to account for the cloud motions on your model? Further, do you assume that this energy is in the form of protons or electrons? (This can be important because the energy losses for the electrons are larger.)

Woltjer answers: The minimum energy could, I think, be reduced to around 10^{51} erg. Protons seem more likely than electrons.

T. K. Menon: High-resolution radio observations (cf. Baldwin, Paper 56, Section 6) have now quite well established that, except for the Crab Nebula, all *radio sources identified with supernova remnants* have the same structure: an incomplete, elongated shell. The structure is similar for both young and old remnants. Hence, from now on it would be appropriate to consider all remnants as being of one class, with the exception of the Crab Nebula.

L. Biermann: The *energy balance* of the neutral hydrogen gas, and specifically the *relative merits of* H II *regions and of supernovae* in maintaining it against the losses in cloud collisions, have been a subject of discussion on many occasions since the Cambridge Symposium of 1953. Kahn has described recent work which leads to values of some fraction of 1% for the efficiency of the process—both for the conversion of the UV quanta produced by OB stars into cloud motions, and for the use of the energetic particles produced by supernovae. We should therefore compare the energy output of early-type stars with that of supernovae, both summed over the volume of the Galaxy, and averaged in time. The energy output of early-type stars should be of the order of 10% of the sum of the thermal radiation of all stars. If this estimate is accepted also for the supernovae, it would appear that H II regions and supernovae are of comparable importance, and the

sum of their contributions might be adequate, particularly if the loss in cloud collisions is reduced by magnetic fields, as seems likely and was discussed also by Pikel'ner (Paper 20).

L. Spitzer: In connection with Biermann's comment, I might point out an advantage of the supernova explanation for interstellar cloud velocities, and that is the uncertainty of the total energy available. The total ultraviolet luminous output from early-type stars is known to at least an order of magnitude, but the total energy released in a supernova explosion is very uncertain, and if one wishes one may increase the energy radiated in visible light by several powers of ten to obtain a suitable amount of energy that might conceivably be available in some form to accelerate interstellar clouds.

M. Schmidt: The constant thickness of the galactic neutral-hydrogen layer over a large range (4 to 10 kpc) of galactocentric distance R, together with the strong increase of total mass density, and hence of K_z, toward the interior of the Galaxy, require that the average peculiar velocity of the clouds increases toward the centre. Since the energy loss goes as v^3, it will be several times larger at $R = 5$ kpc than at $R = 10$ kpc. The energy input from either H II regions or supernovae of type II should depend little on R, because the distribution of these objects over the face of the Galaxy is essentially uniform. Hence, even if energy balance did exist at one place in the Galaxy, it probably does not exist elsewhere. This objection to the importance of energy input by H II regions or supernovae perhaps would not apply to Pikel'ner's magnetic-pressure model, namely if in this model the loss of energy does not increase toward the centre of the Galaxy.

H. van Woerden, in answer to Schmidt: The *thickness of the hydrogen layer* is not constant throughout the Galaxy. While your work (Schmidt 1957) gives an effective thickness (on the new distance scale) of 330 pc at $R = 4$ to 8 kpc, I find (Van Woerden 1967) from Westerhout's (1957) cross-sections perpendicular to the plane an effective thickness of 750 pc at $R = 11$ to 15 kpc. The former value even appears to be an overestimate, in consideration of the new determination by Kerr (1964). This variation of layer thickness affects your arguments about the energy supply and dissipation.

Schmidt replies: I believe that the small increase of the layer thickness from the regions at $R = 4$ to 8 kpc to the solar neighbourhood at $R = 10$ kpc would perhaps somewhat relieve but not invalidate my arguments. Admittedly, this discussion ought to be done quantitatively, on the basis of the observed layer thickness and of a mass model of the Galaxy.

Woltjer comments: In Schmidt's discussion of the layer thickness and cloud motions it is assumed that the cross-section of a cloud is constant through the Galaxy. Until we understand what determines cloud densities we may have some latitude there.

J. H. Oort adds: In connection with Schmidt's assumption of a strong increase of K_z toward the galactic centre, I wish to point to the uncertainty of the model of the mass distribution. K_z is mainly determined by the density in the *disk*. We cannot be certain that this disk density increases very much between $R = 10$ and $R = 5$ kpc.

S. B. Pikel'ner: The observed increase of the thickness of the gas disk or of the spiral arms from the central part of the Galaxy outwards is naturally explained with the magnetic field as a force which maintains the gas. In this model the thickness $\Delta z \sim H(\rho_g \rho_t)^{-1/2}$, where ρ_g is the gas density and ρ_t is the total mass density. The stellar density is much

larger in the central regions, and Δz is less there than near the Sun. In the outer parts $\rho_g \approx \rho_t$, but ρ_g there decreases with increasing R; consequently Δz increases further. If the thickness of the gas layer is the result of the velocity dispersion of the clouds only, it would be difficult to explain the observed effect, as the number of O stars and supernovae is smaller in the outer parts and hence the thickness there should be less.

C. Heiles: The radio determination of the gas-layer thickness depands in part on the assumed temperature of the gas. For example, if the temperature decreases systematically toward the galactic centre, the gas density near the plane in the inner parts may be underestimated, and the thickness consequently overestimated, as a result of optical-depth effects.

H. C. van de Hulst: Coming back to the subject of this section, which is *interstellar clouds*, I am puzzled by the fact that Van Woerden (Paper 1), after saying that it was impossible to define an individual cloud, proceeded to distinguish between internal and external velocities. And Kahn even stated at one place in his review (Paper 15) that a certain theory about the distribution of cloud masses was 'in agreement with observation'. My own suggestion to solve this puzzle is never to take size or mass of a cloud as the starting point or end point of a scientific argument, but rather to refer to those observational data about the cloudiness of the medium which appear most appropriate to the type of theoretical use (e.g., estimate of dissipation of energy by collisions) one wishes to put them to.

Van Woerden: I think I agree for 95%. But there is some misunderstanding. Although the interstellar-cloud concept is ill-defined, I believe I have shown that individual clouds may – given a particular kind of observations, analyzed in a specific manner – quite well be outlined and discussed. My main point was that there is a variety of structures in the interstellar medium, a wide range of sizes and shapes and densities, and that the concept of a *standard* interstellar cloud is of little value. This is the reason why I have *not* given figures for *the* diameter or *the* mass of an interstellar cloud. If I have given definite figures for velocity distributions, it is just because the observations indicate these figures rather consistently; there may be less variety in the motions than in the structures. But I am very much behind the statement that I should not conclude my argument with a set of standard numbers for the structure of an interstellar cloud to give to Kahn to start a theory about.

Heiles: I wish to remind the audience that the gas structure in the region I studied – one out of a half dozen regions which have been well examined – is *not* dominated by clouds.

Van Woerden: Heiles himself has (Paper 5) found a variety of structures in the region analyzed by him. Among these are some that are quite well outlined, although their density excess over the surroundings appears to be low. Which of these structures one should call clouds is again a matter of definition.

REFERENCES

Daniel, R. R., Durgaprasad, N. 1966, *Progress theor. Phys.*, Osaka, **35**, 36.
Field, G. B., Saslaw, W. C. 1965, *Astrophys. J.*, **142**, 568.
Kerr, F. J. 1964, IAU Symposium, no. 20, *The Galaxy and the Magellanic Clouds*, Eds F. J. Kerr and A. W. Rodgers, p. 81, Austr. Acad. Sci., Canberra.
Schmidt, M. 1957, *Bull. astr. Inst. Netherl.*, **13**, 247.
Van Woerden, H. 1967, *Bull. astr. Inst. Netherl.*, in preparation.
Westerhout, G. 1957, *Bull. astr. Inst. Netherl.*, **13**, 201.

Part II

LARGE-SCALE DISTRIBUTION AND MOTION OF THE INTERSTELLAR GAS

'One has to simplify the problem beyond all recognition to get anywhere.'

K. H. Prendergast, in Paper 51

I.A.U. Symposium no. 31, 1967

Chapter II A

Distribution and Motions of Gas in the Disk

CHAIRMAN: B. J. Bok

(*Steward Observatory, University of Arizona, Tucson, Arizona, U.S.A.*)

'The measurements have been corrected for everything you correct such measurements for.'

G. Westerhout, in Paper 28

24. DISTRIBUTION AND SYSTEMATIC MOTIONS OF NEUTRAL HYDROGEN*

(Introductory Report)

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ABSTRACT

Recent work on the rotation curve of the Galaxy has confirmed the large-scale asymmetry of the motion of neutral hydrogen. In addition it seems that the radial velocities at the subcentral points of the lines of sight vary with longitude in a rather unsmooth manner. These irregularities of the motions may be associated with the distribution of matter in spiral arms. Large-scale systematic deviations from circular motion, ranging up to at least 30 km/sec in the outer regions of the Galaxy, are shown by observations across the anti-centre.

Thus it presumably is impossible to describe the velocity field of the gas in terms of a simple general model, or to derive the force field without simultaneously solving the distribution problem. We may have to construct for each region, or for each separate feature of galactic structure, a special model that explains its radial-velocity properties. All these models must of course be in mutual agreement.

The most coherent picture of the large-scale motion of the interstellar hydrogen is still given by the early Dutch and Australian surveys. A number of surveys with higher resolution are at present well on their way, although most of them are limited to a rather narrow strip along the galactic equator.

In the interpretation of line profiles some method of analysis into Gaussian components is increasingly used, especially as an aid in following different structural features in diagrams giving velocity as a function of galactic longitude or latitude, and in separating these features in regions of velocity overlap. Applications of this technique and of simple model-making

*This review is restricted to the regions with $R > 4$ kpc. The central region of the Galaxy is discussed by Kerr in Paper 42.

are demonstrated in connection with a discussion of the local and outer structure of the Galaxy.

Large-scale deviations from the galactic plane as found in recent work indicate that the 'bending' of the plane may be a complicated phenomenon. New observations outlining the true character of this bending are necessary for a decision between the different theories about these deviations.

The need for surveys with high frequency resolution and extending away from the galactic plane is emphasized. Optical identifications of members of the various structural features are highly desirable as an independent determination of parameters of structural models.

1. AN OVERALL VIEW OF THE GALAXY

The most coherent overall picture of the large-scale motion of neutral hydrogen in the vicinity of the galactic plane is still given by the early Dutch and Australian surveys carried out in the 1950's (Van de Hulst *et al.* 1954, Kwee *et al.* 1954, Muller and Westerhout 1957, Westerhout 1957, Schmidt 1957, Kerr *et al.* 1959, Kerr 1962). The most reasonable map of the general distribution of neutral hydrogen that has been derived from these surveys is that presented by Kerr and Westerhout (1965) in Volume 5 of *Stars* and *Stellar Systems* (Figure 1). This map is based on the assumption of circular motions in a steady, axially symmetric gravitational field of central forces. Further the standard solar motion is adopted. The map contains four regions where the methods of observation and of reduction have been different and thus it is not wholly self-consistent. The lines of discontinuity can also be discerned in the structure.

This map is familiar to everybody, but for the sake of clarity I will here mention the labelling of the different *arms* that will be used in this report. The local spiral arm in which the Sun seems to be situated is called the Orion Arm by the Dutch group. We shall here divide it into the 'Orion Arm proper', which consists of the small local half-loop that surrounds the Sun on the outer side (1), the 'Cygnus Extension' (2), and the 'Carina Extension' of the Orion Arm (3). At about 3 kpc outside the Sun we have the prominent Perseus Arm (4). It can be shown rather convincingly, as we shall see later, that the continuation of the Perseus Arm is the outer strong feature in the longitude range 200° to 240° (5). Outside the Perseus Arm we can see the 'Intermediate Arm' (6) and the 'Outer Arm' (7). Inside the Sun we have the northern (8) and southern (9) parts of the Sagittarius Arm, and closer to the centre the Scutum (10) and Norma (11) Arms.

2. HIGHER-RESOLUTION SURVEYS

While this overall picture rests on observations of moderate resolution obtained about ten years ago, several large-scale surveys along the galactic plane made with instruments with higher resolution are at present well advanced towards completion; these will greatly enlarge our knowledge of the systematic motions of the neutral hydrogen. At this Symposium, Westerhout has distributed copies of the very detailed contour maps obtained with the 300-foot (91-m) transit telescope at Green Bank. The effective band-width is 2 km/sec between half-power points, and the survey covers a region from $l = 11°$ to $l = 235°$ between $b = -1°$ and $b = +1°$. Rickard (1965) has made a preliminary discussion of a part of the survey. Westerhout will give more details in a separate communication (Paper 28).

Likewise, Kerr (Paper 26) will present here his survey with the Parkes 210-foot (64-m)

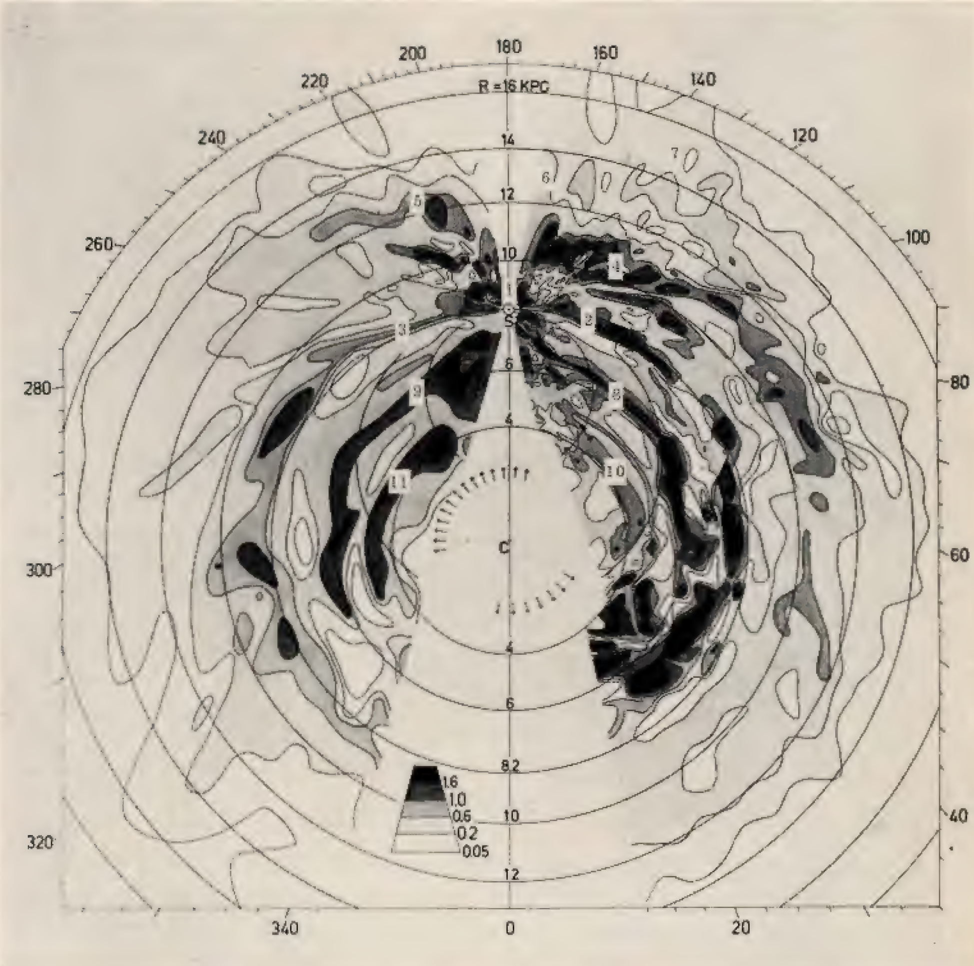

FIG. 1. Distribution of neutral hydrogen in the Galaxy according to Kerr and Westerhout (1965). Figures are inserted to identify certain structures discussed in the text. The inset near the bottom indicates hydrogen densities in atoms per cm³. The scale of the radius has to be slightly enlarged to agree with the new value, 10 kpc, for the Sun's distance from the galactic centre.

telescope. It extends from $l = 300°$ to $l = 63°$, with a range in latitude generally from $b = -2°$ to $b = +2°$. Hindman is extending this survey to include the region from $l = 185°$ to $l = 300°$. A preliminary discussion of some of the results has been given by Kerr and Hindman (1966).

Shane (Paper 29) will describe the survey made by him, Burton and Katgert with the Dwingeloo telescope of a region from $l = 22°$ to $l = 66°$. This survey is now being extended down to $l = 0°$.

Close to the plane of the Galaxy we further have a number of surveys of smaller regions, such as Monoceros (Raimond 1966*a*, *b*), Orion (Van Woerden 1962, 1967) and the anticentre (Höglund 1963; P. O. Lindblad 1966*b*, 1967). In addition there are a number of surveys at intermediate and high galactic latitudes; these are discussed in more detail by Van Woerden (Paper 1) and Blaauw (Paper 45). We should also especially mention the low-resolution survey of the entire southern sky made in Sydney (McGee and Murray 1961, McGee *et al.* 1963, McGee and Milton 1964).

3. THE ROTATION CURVE

One of the fundamentals in the derivation of the distribution of matter in the Galaxy is the establishment of a rotation curve. If the angular velocity $\omega(R)$ is a decreasing function of R and if the motions are circular, then the maximum radial velocity along a line of sight through the inner region is reached at the point closest to the centre of the Galaxy. This has generally been called the 'tangential point'. In order to avoid confusion with the case where a spiral arm is hit tangentially by the line of sight, we will here use the term *subcentral point*. As the velocities may deviate from circular motion and the restrictions laid on ω above may not be valid everywhere, and because neutral hydrogen might be absent at the subcentral point, we must distinguish between three different relations. The *run of terminal velocities* is the run of observed radial velocity, corrected to the galactic standard of rest, as a function of longitude for a suitably defined high-velocity edge of the line profile. By the *apparent rotation curve* we will here understand the set of actual velocity components $\Theta(R)$ at right angles to the radius vector valid for the set of subcentral points. Finally, by the *true rotation curve* we will understand the set of *circular velocities*, $\Theta_c(R, \theta)$, which by definition describes the central force field

$$F(R, \theta) = \Theta_c^2/R. \tag{1}$$

If the force field is not central, it has no meaning to speak about a true rotation curve.

Recent observations by Kerr (1964) with the Parkes telescope on both sides of the galactic centre have clearly demonstrated the difference between the run of terminal velocities as observed on the northern and on the southern side of the centre (Figure 2). Kerr's original suggestion was that this difference might be caused by an outward motion of the local standard of rest. This, however, would imply a similar outward motion for the Orion and Perseus Arms and is contradicted for instance by optical determinations of the systematic motions of Me variable stars (Feast 1963, 1964). Furthermore it does not explain why the difference vanishes for $|l| < 30°$.

If, following Kerr (1962), we do not wish to accept in the hydrogen distribution a virtually empty region along the southern subcentral points, there must then be a *difference between the apparent rotation curves on the northern and southern sides*, caused by large-scale systematic deviations from circular motion, amounting to at least 5 km/sec

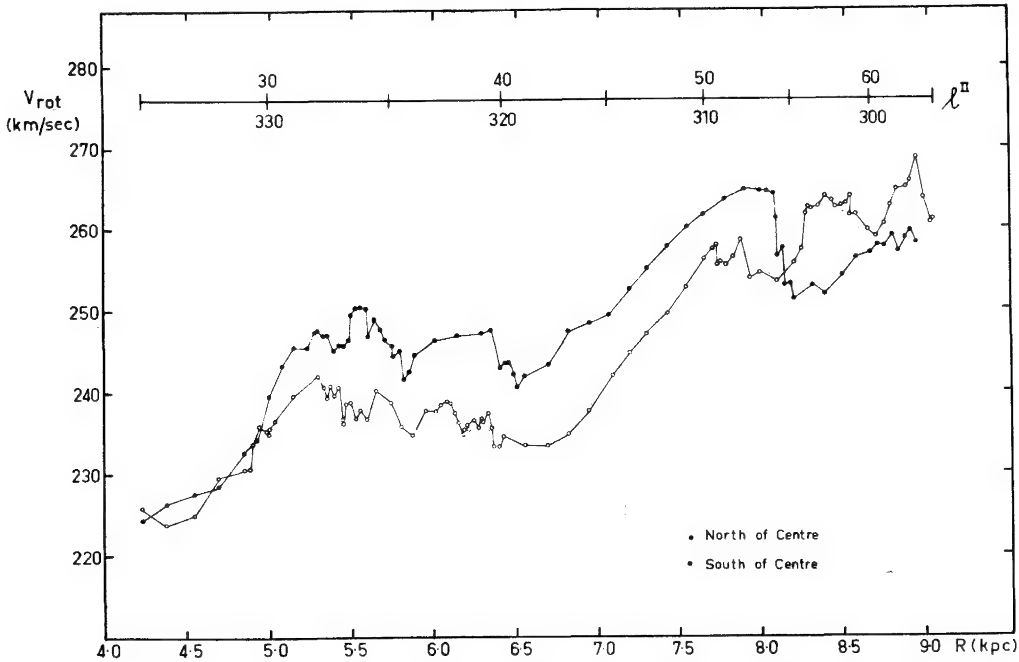

FIG. 2. The run of terminal velocities according to Kerr (1964). Note the differences between the runs obtained on the northern (0° < l^{II} < 90°) side and on the southern (270° < l^{II} < 360°) side of the galactic centre.

in the tangential direction. It is of course not necessary from this evidence alone to conclude that the true rotation curves differ by the same amount, or at all, or that the central force field would not be axisymmetrical.

As a possible flow pattern of slightly noncircular orbits that would reproduce the observed asymmetry of motion, we may imagine an alignment of so-called 'special orbits' (B. Lindblad 1958); a full amplitude of the epicycles of only 200 pc would suffice.

Shane and Bieger-Smith (1966) have published a very thorough discussion of the *rotation curve on the northern side* of the galactic centre (that is, for 0° < l < 90°), based on observations with the Dwingeloo telescope. To derive the (apparent) rotation curve they fit a number of models to the high-velocity ends of their line profiles. The two most important models are number V and number VII. Model V assumes a smooth rotation curve and ascribes the irregularities in the set of observed terminal velocities to variations in the hydrogen densities alone. The terminal velocities then give the space distribution of the edges of the arm structures, i.e. those edges that are turned towards the locus of subcentral points (Figure 3). The observations are confined to the galactic plane and it is not possible to say if the edge should be on the near or far side of this locus. The map is drawn under the assumption of trailing arms, and the jump from the near to the far side is supposed to occur at maximum distance from the locus of subcentral points. The map gives *limits* for the extension of the Sagittarius and Scutum Arms. It does not delineate the arm structure; for instance, the points where the arms are hit tangentially by the

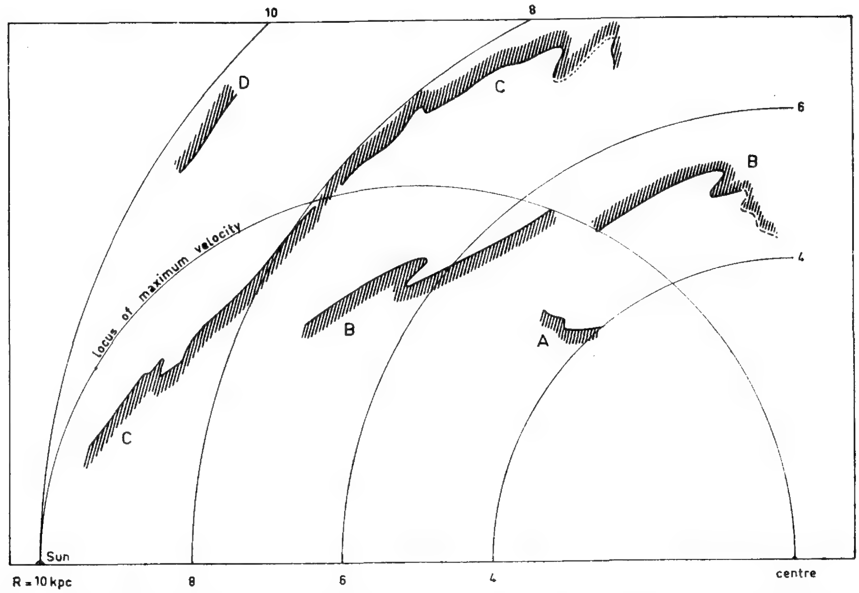

FIG. 3. Edges of spiral arms according to model V of Shane and Bieger-Smith (1966).

lines of sight do not enter into this picture. However, Shane and Bieger-Smith demonstrate that, in order not to show up in the line profiles, the gas around the locus of subcentral points in the inter-arm region must have a density less than one-hundredth of that in the spiral arms, and that regions of intermediate density must be rare. This leads the authors to the conclusion that the apparent rotation curve (as defined here) cannot be smooth.

Thus they reject model V and construct a model VII. In this model the matter at the high-velocity edge of the line profile for each longitude is placed at, or in the immediate neighbourhood of, the subcentral point; Shane and Bieger-Smith attribute the irregularities in the run of terminal velocities to *large-scale streaming motions*. This leads to the rotation curve marked 'model VII' in Figure 4. The optical depths around the terminal peaks give the run of density along the locus of subcentral points shown in the lower part of the figure. There is no trace in this part of the two major spiral arms that one might believe to see tangentially about where the rotation curve shows its two pronounced maxima. In fact, the derived density distribution in the inner region is extremely sensitive to the velocity pattern assumed, and as demonstrated by Shane and Sancisi (private communication) the observed line profiles can be satisfied by almost any density distribution if only a proper field of rather modest deviations from circular velocity is assumed.

It seems rather plausible that the irregularities of the rotation curve are associated with the spiral structure in such a way that there are streams of high or low velocity at different distances from an arm (cf. Burton 1966). If the arms are not circular, the rotation curve would then vary with galactocentric azimuth and a compromise between models of the types V and VII would be conceivable. Shane and Bieger-Smith point out that in this case the interarm regions in Figure 3 would also be regions of low velocity.

Thus, it may be necessary to solve the distribution problem and derive the circulation pattern simultaneously. By a method somewhat related to that of Agekjan and collaborators (1964), we might consider to fit to the entire set of line profiles a model of spiral-arm distribution, giving a value for the ratio of neutral-hydrogen density to total mass density in the arms and including a theory for the circulation of matter in and outside the arms. The extended survey that now is being carefully analysed by Shane and Burton (cf. Paper 29) will tell us more about these possibilities.

4. PROCEDURES FOR THE OUTER REGIONS

As the rotation curve derived by Kwee, Muller and Westerhout (1954), after correction to the new distance scale, for some reason fits rather well as a mean rotation curve for model VII (see Figure 4), it may not be unreasonable to assume that this KMW curve corresponds closely to a true rotation curve freed from the perturing effects of the spiral arms. Consequently, for the regions of the Galaxy outside the Sun's distance from the centre, the new rotation curve for circular velocities derived by Schmidt (1965) may still be a resonable first approximation to the true rotation curve. However, large-scale systematic deviations from circular motion in the outer parts of the Galaxy, ranging up to at least 30 km/sec, are shown by observations across the anticentre region. Thus, in order to find the spatial distribution we also here must construct models, and perhaps different models for different structural features to account for their behaviour in the velocity-longitude diagram. Some examples of such models will be given later.

Abandoning the idea of purely circular motion, we have to go back to the original observations and trace out the different features of galactic structure in velocity diagrams of various kinds. To give an overall impression of the kind of velocity pattern we are dealing with, I have prepared the contour diagram in the velocity-longitude plane shown in Figure 5. It is pasted together from pieces of the old Kootwijk survey (P. O. Lindblad 1966*a*), from the map of Shane and Bieger-Smith (1966), and from the new surveys by Kerr and Hindman (1966 and private communication). It is very inhomogeneous, which to some extent illustrates the present state of affairs. By a comparison with Figure 1 we recognize the observational basis for the different features of galactic structure.

In the delicate task of separating and tracing different structural features we must consider all their measurable properties. As an aid to do this in regions of velocity overlap, some method of 'Gaussian analysis' is often employed. I will demonstrate some advantages of this technique as applied to the anticentre region, where the overlapping problem is particularly serious (P. O. Lindblad 1967), and on this basis discuss the local and outer structure of the Galaxy.

Figure 6 shows two series of line profiles obtained with the Dwingeloo telescope in sections perpendicular to the galactic plane through the anticentre region. The principal maximum of the profiles is mainly composed of contributions from the Perseus and Orion Arms, but we note that the edge towards positive velocities is steep and that even at low latitudes the maximum is double-peaked; this gives the impression that we might here have a narrow component with a positive velocity of somewhat less than 10 km/sec. At the negative-velocity side we see a secondary maximum especially pronounced at $l = 177°$, $b = -2°$. This is due to the Intermediate Arm (cf. Figure 1). Furthermore we see a number of features below the plane with negative radial velocities. In particular, the pronounced maximum at $b = -9°$ with a velocity of -30 km/sec is an extension of the Outer Arm.

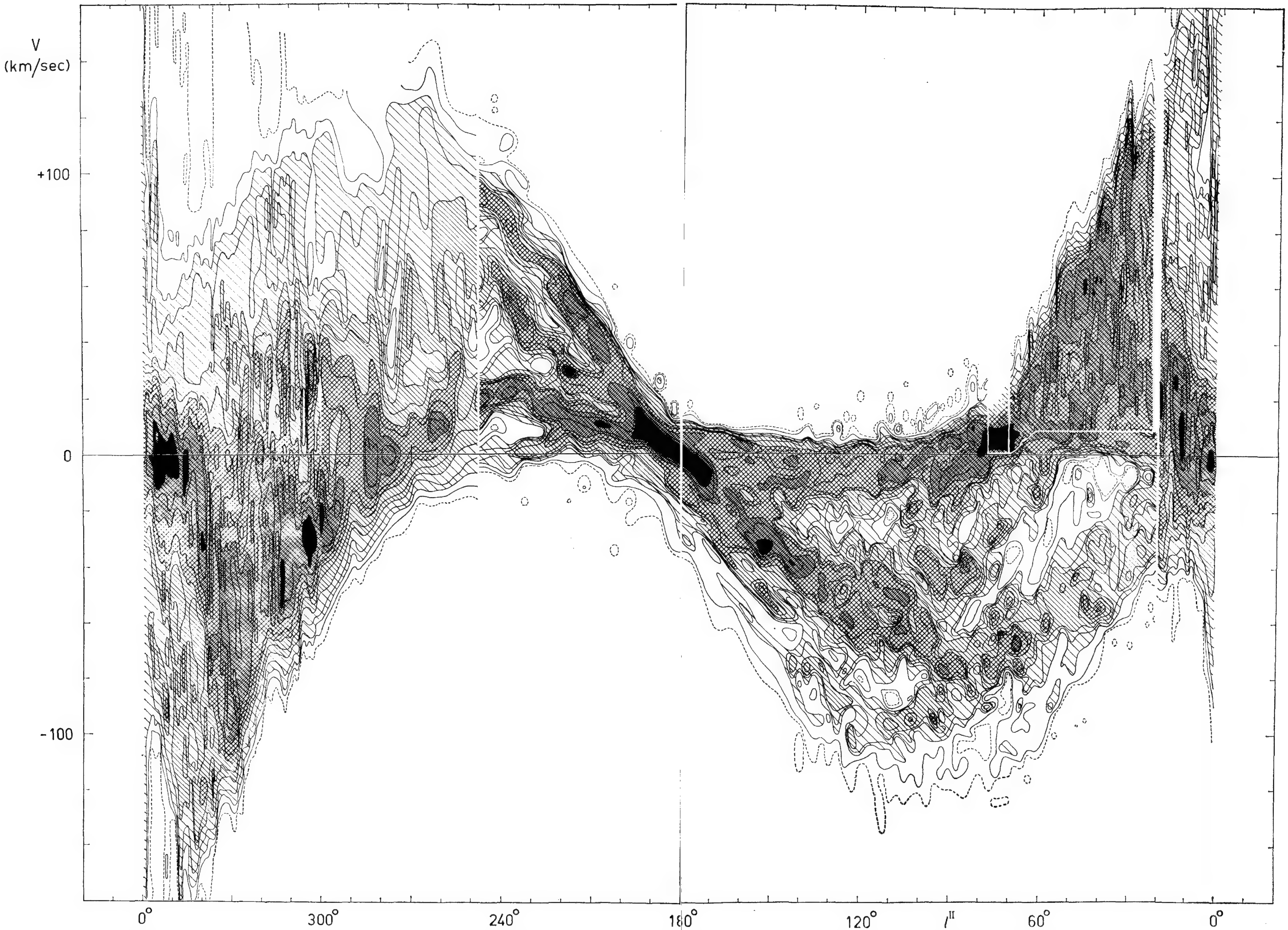

FIG. 5. General velocity-longitude diagram for neutral hydrogen close to the galactic plane, as combined from various surveys. Shadings indicate intensities or optical depths in the 21-cm line. The scale is qualitative only; it has been adjusted between the different surveys.

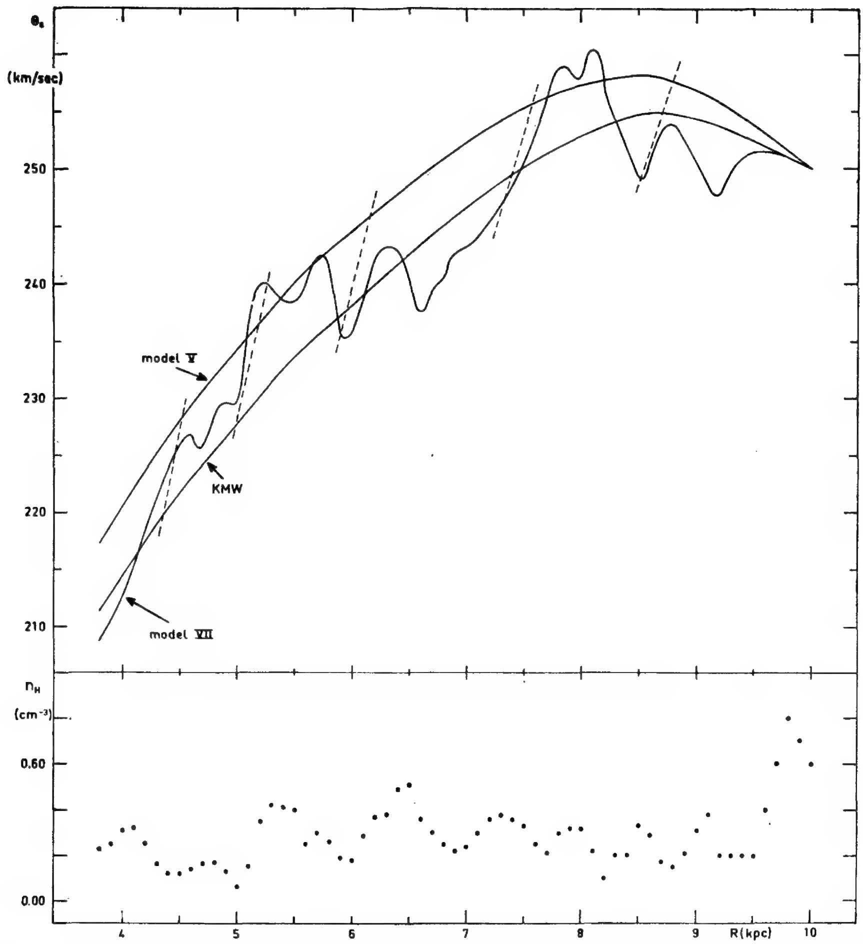

FIG. 4. The upper part of the figure shows the apparent rotation curves for models V and VII of Shane and Bieger-Smith (1966), along with the rotation curve derived by Kwee, Muller and Westerhout (1954) as corrected to the new distance scale. The lower part shows the run of neutral hydrogen density along the locus of subcentral points adopted for model VII. Note that the notation Θ_c (R) for the apparent rotation curve deviates from that in the text.

a. Gaussian analysis, and features outlined by it

In order to separate as far as possible these different features, the line profiles have been analysed in terms of *Gaussian components*. Figure 7 shows a typical sample of the fits obtained. It indicates that in general the observed profiles can be very accurately represented by a very limited number of Gaussian components. Figure 8 illustrates the sets of components for the profiles reproduced in Figure 6. A Gaussian component is here represented by a box, with a length equal to twice the dispersion and a height proportional to the maximum optical depth. One cannot caution enough against too hasty

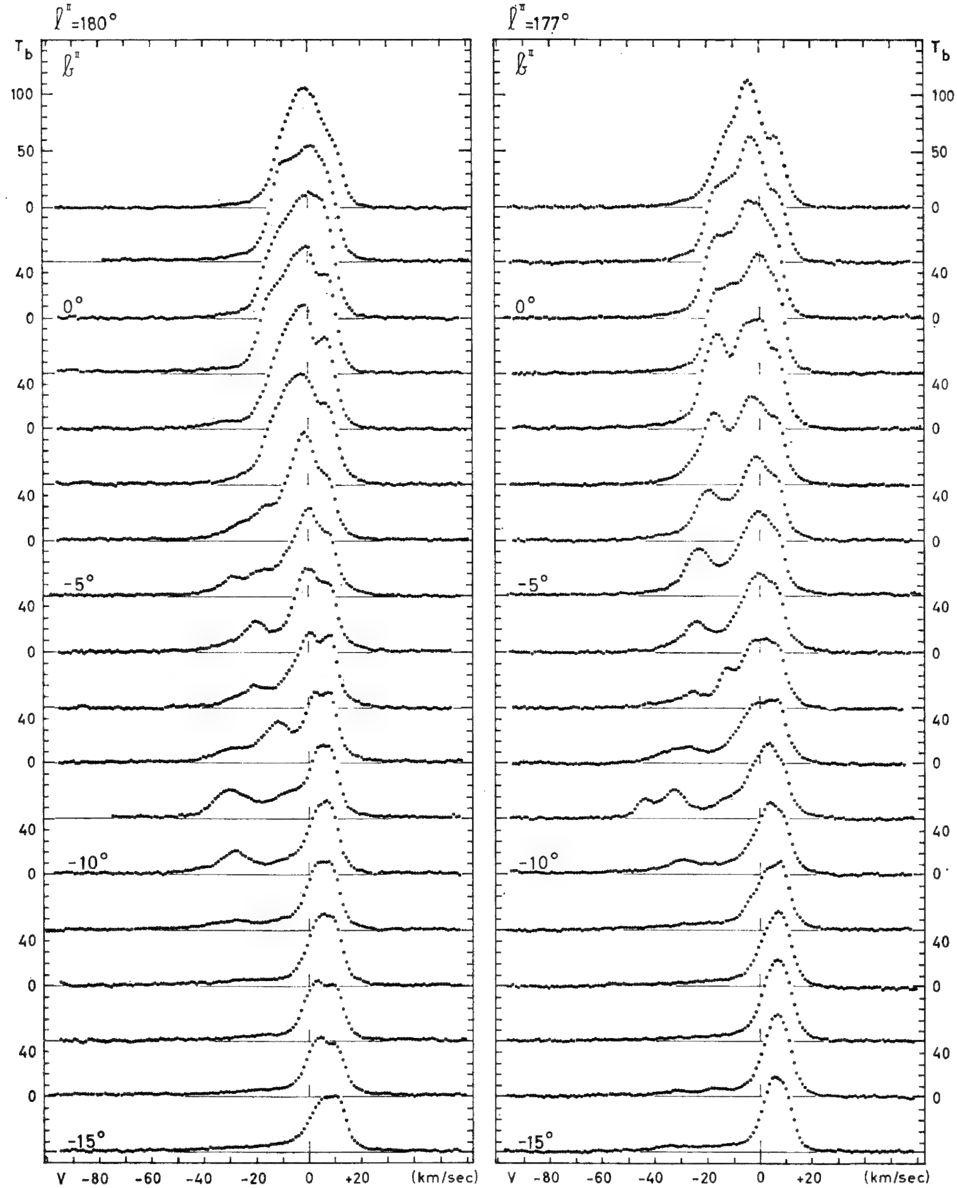

FIG. 6. Line profiles close to the anticentre direction as observed at Dwingeloo in two sections perpendicular to the galactic plane (P.O. Lindblad 1966*b*).

conclusions from Gaussian analyses, and to analyse a single profile may in many cases have no physical meaning. The working hypothesis to be adopted here is the following: if we can trace a component on the sky, where its dispersion keeps constant, its velocity is constant in latitude and varies smoothly with longitude, and its intensity shows a smooth variation with latitude and almost no variation with longitude, then such a component or combination of components is supposed to represent a 'feature' of galactic structure. (As an example, note in Figure 8 feature A with its very small velocity dispersion and practically no variation of intensity with latitude within this interval; the Perseus Arm (E) and Orion Arm (C) cannot be separated, except for their different latitude distributions.) One of the big advantages of Gaussian analysis is that it supplies a basis for numerical treatment, comparison and averaging of different line profiles.

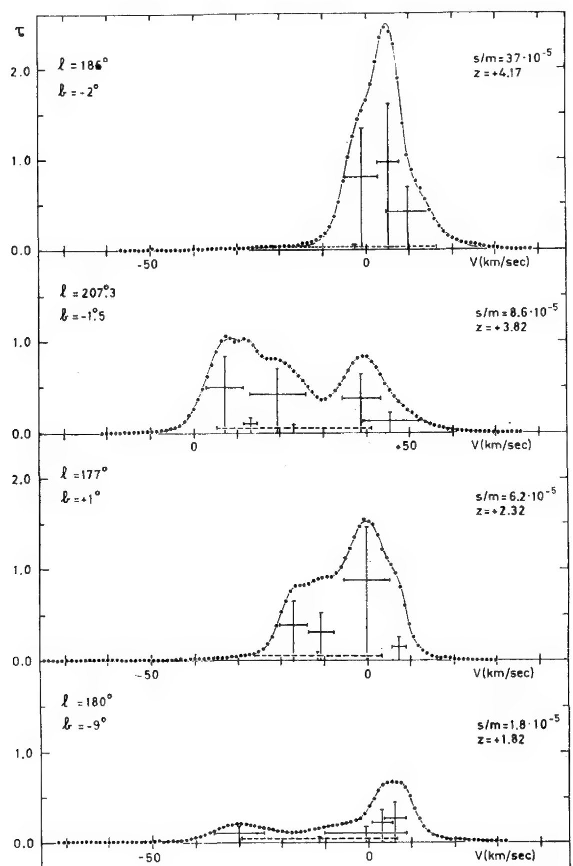

FIG. 7. Typical examples of Gaussian analysis (P.O. Lindblad 1967). Solid dots are recorded measurements along the observed profile. Gaussian components are represented by crosses, with a height equal to the maximum optical depth and a cross-beam equal in length to twice the velocity dispersion. The fulldrawn curve gives the sum of the Gaussian components.

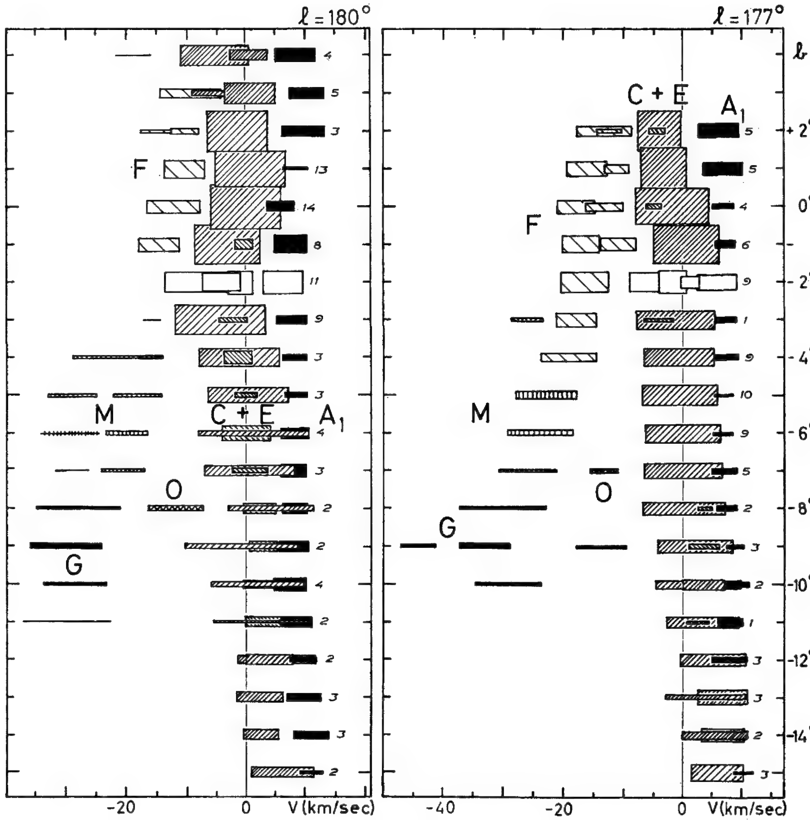

FIG. 8. Results of a Gaussian analysis of the two series of profiles shown in Figure 6. Each Gaussian component is represented by a box, with a length equal to twice the velocity dispersion and a height proportional to the maximum optical depth.

Averaging in latitude for the different longitudes we get from this analysis the squares and rectangles of the component map of Figure 9. Circles are read from the Kootwijk Survey (P. O. Lindblad 1966*a*) and triangles from observations by Höglund (1963).

In the separation of the different *features*, A distinguishes itself by its small velocity dispersion of only 2 km/sec and its large extent in latitude. It has a velocity of +8·5 km/sec at the anticentre. C/H is the local part of the Orion Arm proper (feature 1 in Figure 1) and has a half-intensity width of about 18° in latitude. Feature E is the Perseus Arm. A comparison of latitude dependence of the hydrogen densities, of maximum densities and of velocity dispersions strongly favours its continuation in the L-arm, in agreement with the original interpretation by Westerhout (1957). Feature F is the Intermediate Arm, which shows a velocity (of approach) of −11·4 km/sec at the anticentre. It shows some similarities with the I-arm, but the connection is uncertain. M and O are features that lie 5° and 8° below the galactic plane respectively. Feature G, finally, is the continuation of the Outer Arm. It dives down to $b = -9°$ at the anticentre, where

it shows a velocity (of approach) of $-29{\cdot}5$ km/sec. At $l \approx 190°$ it disappears among the low-velocity gas, but seems to reappear again at $l \approx 220°$ and about the same latitude. Its angular width in latitude is on the average 2° between half-density points.

b. Discussion of the structural features

In the discussion of these structures we will start with what appear to be the local features and move outwards. *Feature A*, with its small velocity dispersion and large angular extent, gives the impression to represent one single local cloud. It has not been presented in any maps of galactic structure, because its velocities cannot be mapped on the assumption of circular velocity. The velocity-longitude relation is shown in Figure 10. It proves that this relation shares some of the characteristics of configurations expanding while under the influence of differential galactic rotation. The curve drawn in the figure is the radial-velocity curve of an expanding ring of stars viewed from an excentric point inside the ring, where the original velocity of expansion is 6 km/sec and the expansion age 6×10^7 years. It is tempting to connect this feature with the expansion of the local group of early-type stars as demonstrated by Blaauw (1965) and Bonneau (1964).

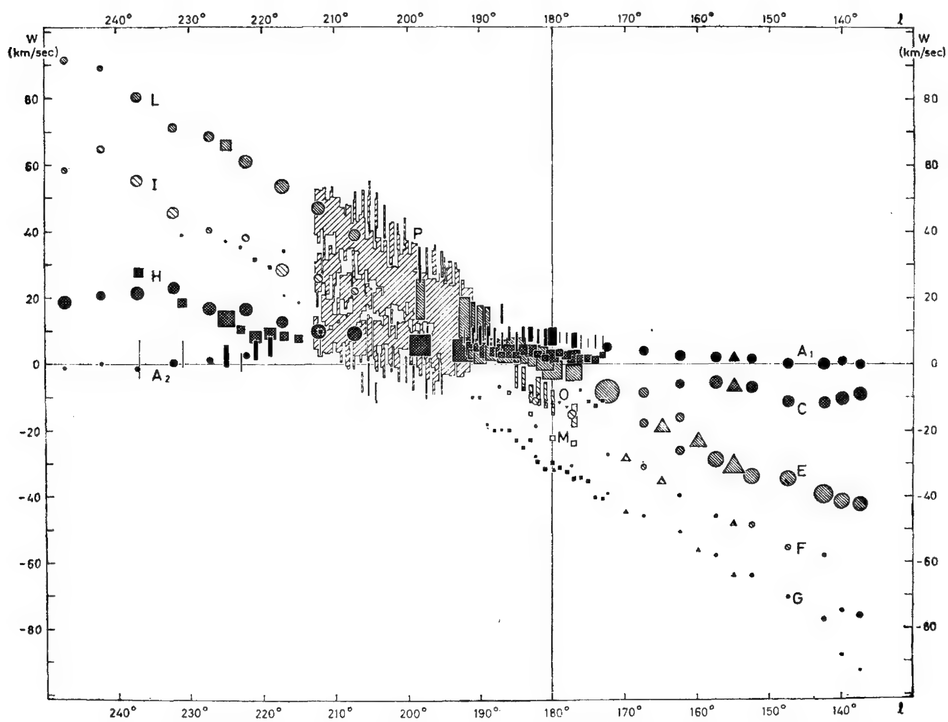

FIG. 9. General diagram of radial velocity vs. longitude across the anticentre region (P.O. Lindblad 1967). Rectangles, squares and small triangles pointing down represent mean values (averaged over galactic latitude) of components resulting from the Gaussian analysis of Dwingeloo observations. Circles give velocities as derived from the Kootwijk survey and triangles pointing up come from observations by Höglund (1963).

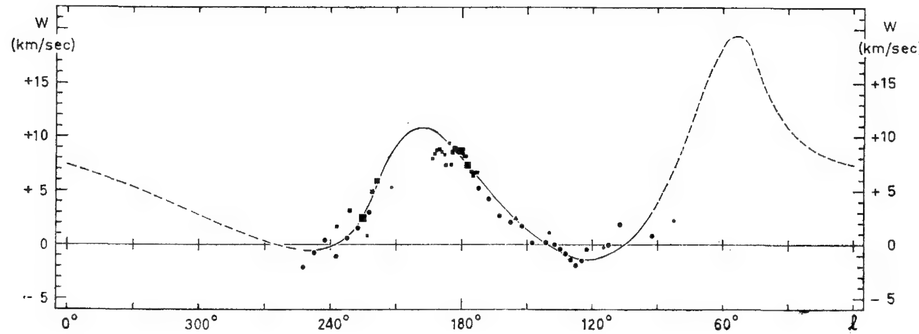

FIG. 10. Velocity-longitude relation for feature A (P. O. Lindblad 1967). The curve drawn through the observations is the theoretical relation for the expanding configuration described in the text.

The well-observed part of the *Orion Arm*, C/H in Figure 9, shows a characteristic double sine wave; this gives it, in a map based on the assumption of circular velocities, the appearance of one half of an elongated ring surrounding the Sun. The *Cygnus Extension* of the arm runs through a region where distance determinations are very sensitive to small deviations from circular motion. Its run in the Leiden map was drawn after a study of the difficult region around $l = 90°$. However, it is seriously mixed there with feature A and with a narrow arm that comes in from negative velocities. This region has to be re-observed and carefully discussed before we can be certain about the existence and shape of the Cygnus Extension of the Orion Arm as it usually is drawn in 21-cm maps.

In the direction of the *Carina Extension* of the Orion Arm the situation looks quite different. We have a very strong impression that, when the line of sight sweeps through increasing longitudes, we suddenly hit an arm tangentially at a longitude of about 280° and not that we here are looking along an arm that would pass outside the Sun. We find a discussion of the optical data for the Carina Arm in the recent review by Sher (1965). I take the liberty to present the 'improbable' map of hydrogen structure (Kerr 1962) drawn on the basis of the Kwee-Muller-Westerhout rotation curve (Figure 11). Kerr discarded this map because of the empty region along the subcentral points in the southern part ($290° < l^{II} < 340°$) of the diagram. The rotation curves have been slightly changed since then, so that the innermost part of this rift has probably been filled in. I should like to ask if it would not fit the 21-cm data better to extend the arm that we see tangentially at $l = 280°$ towards the northern Sagittarius Arm, which would also give a better fit with optical data, and if at least part of the difference between the runs of terminal velocities on the northern and southern sides might not be explained by a relatively empty region with a possibly slower rotational motion on the other side of this arm. With this I want to point out that the Orion Arm is one of the greater puzzles in the problem of galactic structure, a puzzle that can be solved only by an extensive set of properly planned observations.

The dominating feature outside the Sun is the *Perseus Arm*. At the anticentre it does not show any significant velocity component in the radial direction. If the motion is

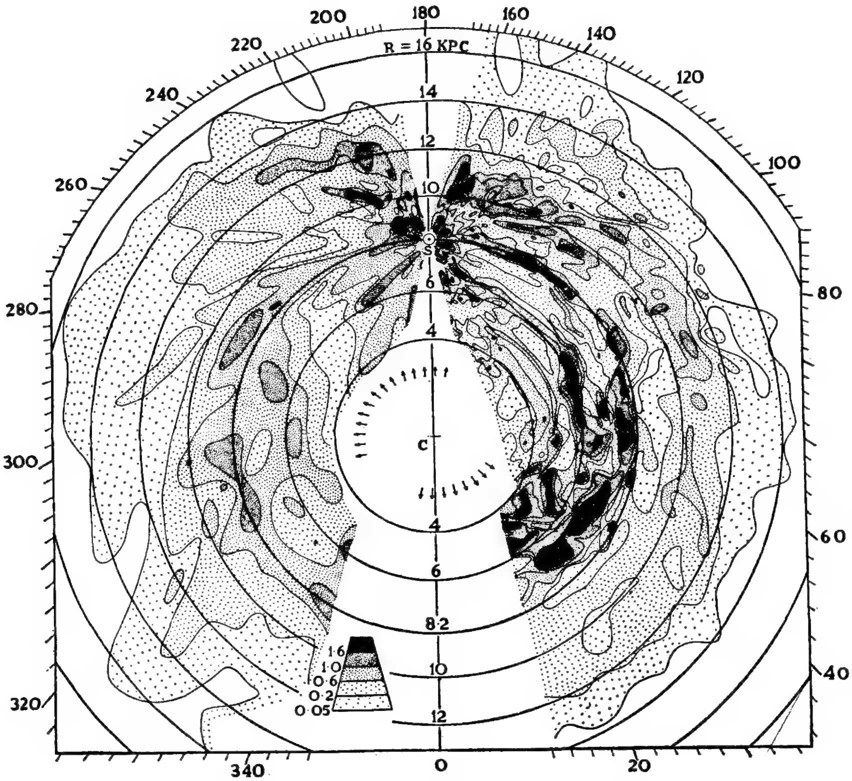

FIG. 11. Distribution of neutral hydrogen in the Galaxy, based on the Kwee-Muller-Westerhout rotation curve (Kerr 1962).

circular, its distance is 3 kpc on the new Schmidt model. This seems to be the only fairly reliable 21-cm distance in our surroundings.

The outer features show large systematic *deviations from circular motion.* As noted before, in order to derive the space distribution we have to make a model that explains the cause of these deviations. The cause may be for instance the Magellanic Clouds, a density wave in the inner region of the Galaxy of the same kind that was mentioned in connection with the rotation curve, or the inclination of the Perseus Arm if this arm is massive enough. We can then set up equations for the perturbed motion of matter containing the parameters of the model; these parameters may be adjusted to give a best fit to the observed part of the velocity-longitude relation. Just as an example we show in Figure 12 a model for the Outer Arm in the case of perturbations by the inclined Perseus Arm. The full-drawn heavy line indicates the well-defined part of the Perseus Arm. The dashed extension is drawn as an Archimedean spiral with the same inclination. Now, a trailing spiral arm will decelerate outer particles and cause them to fall inwards while they at the same time increase their angular velocity. If we assume that we know the shape and state of motion of the Perseus Arm, and that the perturbed arm initially formed part of an outer spiral arm moving with circular velocities, then the four parameters

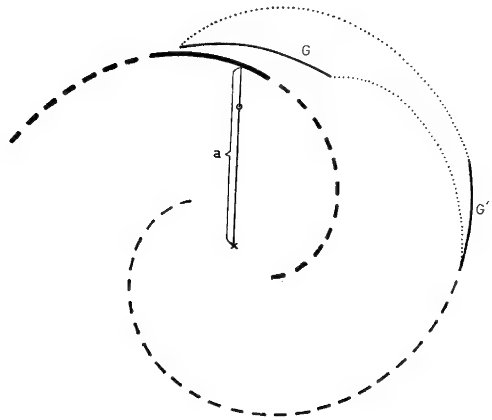

FIG. 12. Model suggested to explain the motion of the Outer Arm. The symbol ⊙ marks the present position of the Sun. The full-drawn heavy line shows the well-defined part of the Perseus Arm, where the distance from the centre $a = 13$ kpc; the dashed extension is a hypothetical continuation of this arm. G′ is the position of the end of the Outer Arm when perturbations by the Perseus Arm become efficient, G its present position.

entering the equations of motion and to be determined by a comparison with the observed velocity-longitude relation are: the total mass density per unit length in the Perseus Arm, and three parameters giving the initial location and shape of the perturbed arm. Observations should supply the density of neutral hydrogen in the Perseus Arm; combination of this with the first parameter gives the ratio between the total density and the atomic-hydrogen density in the arm. The merits of the model could then be judged from the value of this ratio. However, in the present state of observation, with the many assumptions involved, and where the actual shape of the Perseus Arm is very poorly known, it is not possible to arrive at a unique answer.

5. THE BENDING OF THE GALACTIC PLANE

The *Outer Arm* deviates appreciably from the galactic plane, as is seen from the map of Figure 13. (At $l = 173°$, the dividing line between the Kootwijk and Dwingeloo surveys, there is a discontinuity in the resolution in both l and b.) The upward 'bending' of the galactic plane on the northern side (that is, at $0° < l < 180°$) reaches greatest prominence in the continuation of this Outer Arm to lower longitudes. The large deviation of this arm from the plane at the anticentre and the deviations from the plane observed there for other features with different velocities of approach show that this 'blending' of the plane is a rather complicated phenomenon. In an investigation with the Dwingeloo telescope Habing (1966) has examined faint extensions of high-velocity gas up to intermediate latitudes. Since their dependence of velocity on longitude is similar to that of the Outer Arm, he favours the conclusion that these faint structures are an extension of this arm up to 4 kpc north of (above) the plane. However, the coincidence of the velocity curves is not so exact that one *must* assume a relation with the Outer Arm, nor do we know what motions to expect at such distances from the plane. Thus we must also seriously consider

—as indeed has been done by Habing—, that this puzzling feature might belong to the same category as the high-velocity clouds to be discussed by Blaauw and Oort later in this Symposium (Papers 45 and 46).

The *cause of the bending of the plane* has been discussed by various authors. Obviously, the Magellanic Clouds must exert a 'precessional' perturbance on orbits in the Galaxy. If the Clouds describe an orbit around the Galaxy, the net effect of the perturbations, in accordance with classical celestial mechanics, to the first order will be a regression of the nodes of the galactic orbits with respect to the orbital plane of the Clouds. This continued regression of the nodes is what Elwert and Hablick (1965) call the 'resonance component' of the motion. Thus, the galactic orbits would turn around an axis perpendicular to the orbital plane of the Magellanic Clouds. The speed of the regression will increase with the radius of the galactic orbit. If the present maximum deviation is in the direction of the

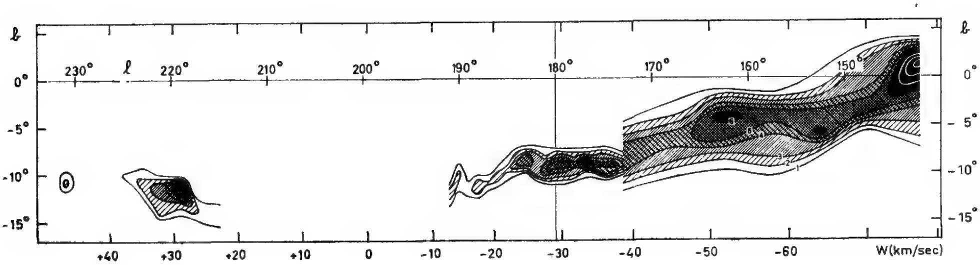

FIG. 13. Surface density as a function of position for the Outer Arm. For $l < 173°$ according to the Kootwijk Survey, for $l > 173°$ according to Dwingeloo observations. The lower horizontal scale indicates mean radial velocities. The isophotes give the surface density with 10^{20} atom/cm^2 as unit.

Clouds, this would as it seems be a pure coincidence. Order-of-size estimates based on a simple model show that, for a favourable orientation of the Clouds' orbit, the time required to tip the Outer Arm to its present inclination is of the order of a few times 10^9 years.

An intergalactic wind that exerts a pressure on the interstellar gas in galactic orbits (Kahn and Woltjer 1959) would tend to turn such orbits around an axis coinciding with the fixed wind direction. The maximum deviation from the plane would first occur 90° from the wind direction as seen from the galactic centre. The situation gets more complicated if the stellar component exerts an appreciable force back towards the plane.

A third explanation has been advanced by Lynden-Bell (1965), who has shown that a deviation between the angular-momentum vector of the Galaxy and its symmetry axis may result in large deviations from the plane around certain values of R.

In order to be able to distinguish between these models we first have to outline in detail the outer rim of the Galaxy and all the features deviating from the plane. If theory requires time scales of the order of 10^9 years to turn these arms out of the plane, we cannot explain the deviations from circular motion or the maintenance of these outer arms by theories that require large-scale circulation and exchange of matter between different arms.

6. CONCLUDING REMARKS

In concluding this review I should like to emphasize strongly the need for more and well-planned observations. For a distinction between different structural features it is necessary to extend the observations to some distance from the galactic plane. Separation of features such as, for instance, the Orion Arm and the supposedly expanding cloud A requires the use of a high frequency resolution in the surveys. A bandwidth of 10 kHz is a maximum, and the optimum may be about 7 kHz. It also is of extreme importance to secure optical identifications of members of the different structural features. This would independently give us some parameters of our models by which we ultimately must derive the entire density distribution.

REFERENCES

Agekjan, T. A., Petrovskaja, I. V., Fesenko, B. I. 1964, *Astr. Zu.*, **41**, 1027 (translation in 1965, *Soviet Astr.*, **8**, 823).

Blaauw, A. 1965, *Verslag gewone verg. Afd. Natuurk. K. ned. Akad. Wet.*, **74**, 54 (in Dutch).

Bonneau, M. 1964, *J. Observateurs*, Marseille, **47**, 251.

Burton, W. B. 1966, *Bull. astr. Inst. Netherl.*, **18**, 247.

Elwert, G., Hablick, D. 1965, *Z. Astrophys.*, **61**, 273.

Feast, M. W. 1963, *Mon. Not. R. astr. Soc.*, **125**, 367.

Feast, M. W. 1964, IAU Symposium, no. 20, *The Galaxy and the Magellanic Clouds*, Eds. F. J. Kerr and A. W. Rodgers, p. 67, Austr. Acad. Sci., Canberra.

Habing, H. J. 1966, *Bull. astr. Inst. Netherl.*, **18**, 323.

Höglund, B. 1963, *Ark. Astr.*, **3**, 215.

Kahn, F. D., Woltjer, L. 1959, *Astrophys. J.*, **130**, 705.

Kerr, F. J. 1962, *Mon. Not. R. astr. Soc.*, **123**, 327.

Kerr, F. J. 1964, IAU Symposium, no. 20, *The Galaxy and the Magellanic Clouds*, Eds. F. J. Kerr and A. W. Rodgers, p. 81, Austr. Acad. Sci., Canberra.

Kerr, F. J., Hindman, J. V., Gum, C. S. 1959, *Austr. J. Phys.*, **12**, 270.

Kerr, F. J., Hindman, J. V. 1966, in *Mount Stromlo Symposium on Radio and Optical Studies of the Galaxy*, Eds. J. V. Hindman and B. E. Westerlund, p. 90.

Kerr, F. J., Westerhout, G. 1965, in *Galactic Structure*, Eds. A. Blaauw and M. Schmidt, Vol. V in the series: *Stars and Stellar Systems*, Univ. of Chicago Press, Chicago, p. 167.

Kwee, K. K., Muller, C. A., Westerhout, G. 1954, *Bull. astr. Inst. Netherl.*, **12**, 211.

Lindblad, B. 1958, *Stockholm Obs. Ann.*, **20**, no. 6.

Lindblad, P. O. 1966*a*, *Bull. astr. Inst. Netherl. Suppl. Ser.*, **1**, 77.

Lindblad, P. O. 1966*b*, *Bull. astr. Inst. Netherl. Suppl. Ser.*, **1**, 177.

Lindblad, P. O. 1967, *Bull. astr. Inst. Netherl.*, **19**, 34.

Lynden-Bell, D. 1965, *Mon. Not. R. astr. Soc.*, **129**, 299.

McGee, R. X., Milton, Janice A. 1964, *Austr. J. Phys.*, **17**, 128.

McGee, R. X., Murray, J. D. 1961, *Austr. J. Phys.*, **14**, 260.

McGee, R. X., Murray, J. D., Milton, Janice A. 1963, *Austr. J. Phys.*, **16**, 136.

Muller, C. A., Westerhout, G. 1957, *Bull. astr. Inst. Netherl.*, **13**, 151.

Raimond, E. 1966*a*, *Bull. astr. Inst. Netherl. Suppl. Ser.*, **1**, 33.

Raimond, E. 1966*b*, *Bull. astr. Inst. Netherl.*, **18**, 191.

Rickard, J. J. 1965, Thesis, Univ. of Maryland.

Schmidt, M. 1957, *Bull. astr. Inst. Netherl.*, **13**, 247.

Schmidt, M. 1965, in *Galactic Structure*, Eds. A. Blaauw and M. Schmidt, Vol. V in series: *Stars and Stellar Systems*, Univ. of Chicago Press, Chicago, p. 513.

Shane, W. W., Bieger-Smith, G. P. 1966, *Bull. astr. Inst. Netherl.*, **18**, 263.
Sher, D. 1965, *Q. J. R. astr. Soc.*, **6**, 299.
Van de Hulst, H. C., Muller, C. A., Oort, J. H. 1954, *Bull. astr. Inst. Netherl.*, **12**, 117.
Van Woerden, H. 1962, De neutrale Waterstof in Orion, Thesis, Univ. of Groningen (in Dutch).
Van Woerden, H. 1967, *Bull. astr. Inst. Netherl.*, in preparation.
Westerhout, G. 1957, *Bull. astr. Inst. Netherl.*, **13**, 201.

Discussion

G. Westerhout: What beamwidth should one use for investigations of galactic structure?

P. O. Lindblad: The optimum beamwidth depends strongly on the type of investigation. While 2°-beams have been useful for overall surveys of the Galaxy, the present beams of 0°.6 and 0°.2 will give important information of a more detailed nature.

B. J. Bok: We should not overlook that many of the results discussed in Linblad's fine paper depend critically upon the values assumed for R_0, the Sun's distance to the galactic centre, and for Θ_0, the circular velocity at R_0. The recent work of H. L. Johnson and associates on interstellar reddening has made us again cautious with regard to the values of R_0 and Θ_0 upon which we all agreed at the 1964 Hamburg meeting of the IAU. Radio astronomers will be wise if they take this new source of uncertainty into account in their work. Optical astronomers should not use without question the standard value 3·0 or 3·2 for the ratio between total visual extinction, A_V, and colour excess, E_{B-V}. It seems highly advisable that photometric work on the *UBV* system should generally be supplemented by measurements in the red and near infrared, *R* and *I*.

(For a further discussion of the ratio of extinction to colour excess, see Paper 25.—*Editor*).

H. J. Habing: I have made numerical calculations on the tidal distortion of the Galaxy by the Magellanic Clouds, to investigate whether such a distortion could explain the bending of the galactic layer of hydrogen gas and, possibly, the extension of the Outer Arm to large distances from the plane (Habing, H. J. 1966, *Bull. astr. Inst. Netherl.*, **18**, 323).

Numerical integrations were obtained of the equations of motion of a number of non-interacting mass points, originally moving in circular orbits around the galactic centre, but then perturbed by the Magellanic Clouds. The Clouds were considered as mass points, moving in an elliptical orbit; from the observed radial velocity it follows that the pericentre distance must be less than 32 kpc (present distance 46 kpc). The Galaxy's gravitational potential was taken invariant; Schmidt's 1956 (*Bull. astr. Inst. Netherl.*, **13**, 15) model of the mass distribution was used.

The results showed that the mass points started oscillating with respect to the galactic plane (defined as the plane of symmetry of the (rigid) central parts of the Galaxy) in a time short compared to the orbital period of the Clouds (2×10^9 years). The amplitude of the oscillation varied with distance R to the galactic centre: 400 pc at $R = 15{\cdot}3$ kpc, 50 pc at $R = 12{\cdot}0$ kpc.

H. C. D. Visser has refined these calculations, using Schmidt's new mass model (1965, *Galactic Structure*, Vol. V in the series: *Stars and Stellar Systems*, p. 527). He computed the oscillations of a small-diameter cylinder perpendicular to the plane. Since all the mass in this cylinder undergoes the same vertical perturbations, only those parts of $K(z)$ originating in the central parts of the Galaxy were taken into account.

The integrations yielded results similar to those mentioned above; the amplitudes of the oscillations were somewhat larger. At $R = 16$ kpc instabilities may occur: mass points

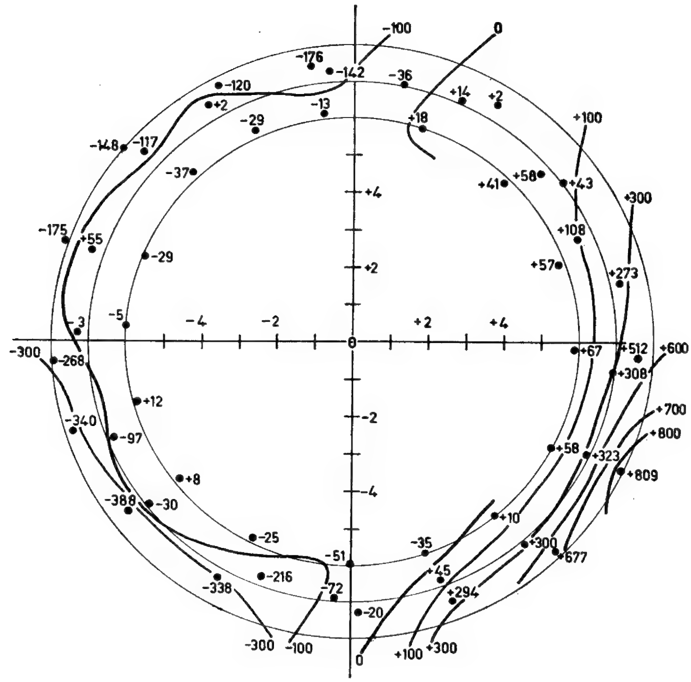

FIG. 14. Projection on the galactic plane of 70 mass points, originally distributed homogeneously in the plane between $R = 12$ and 14 kpc, after they have been perturbed by the Magellanic Clouds for 2×10^9 years (one orbital period). The Clouds have returned to the apogalaktikon, in the lower left-hand corner of the figure, at $R = 61{\cdot}2$ kpc and $z \approx -40$ kpc. The number by the side of each mass point represents its distance (in parsec) from the plane. The scales on the axes are in kiloparsec.

are torn out of the Galaxy. Figure 14 shows the positions after 2×10^9 years. Although in general mass points in the same sector of the Galaxy are either all above or all below the plane, some rings appear to be out of phase. Obviously, in the next approximation, the interaction between neighbouring rings must be taken into account. This may be achieved by numerical calculations of the many-body-problem type, with one mass dominating.

Calculation of the oscillations for mass points starting with various $Z \neq 0$, taking into account the change in $K(z)$ produced by the local distortion of the gas layer, yields no evidence for asymmetries between the amplitudes on either side of the plane.

I.A.U. Symposium no. 31, 1967

25. LOCAL STRUCTURE AND LARGE-SCALE MOTIONS FROM YOUNG OBJECTS

(Invited Paper)

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ABSTRACT

Substitution of the value 3·2 for the ratio R of total visual extinction to reddening leads to a revision of the galactic rotation curve determined by Feast and Shuttleworth. The new results agree very well with the 21-cm rotation curves, particularly with those by Kwee, Muller and Westerhout and by Shane and Bieger-Smith. The corresponding local value for Oort's constant is $A = +15.2$ km sec^{-1} kpc^{-1}.

With the exclusion of special regions like Orion, the ratio R appears to vary only little about an average of 3·2. This value gives a clearer spiral pattern than the strong variations of R with l advocated by Johnson; also it leads to better correlation of velocity with distance at the maxima of differential galactic rotation.

1. INTRODUCTION

Open clusters and highly luminous stars are useful sources of information about the structure and kinematics of spiral arms. The basic *advantage* of such optical studies is knowledge of distance. The basic *problem* at present is the uncertainty in the ratio between total (visual) extinction and reddening. The classical value for $R \equiv A_V/E_{B-V}$ is 3·0. Johnson (1967; see also Johnson and Borgman 1963, Borgman 1966) finds R varying from 3·6 up to 8. From Whitford's (1958) observations in Cygnus and Cassiopeia, I have derived $R = 3·2$ (Schmidt-Kaler 1961). The same value results from Johnson's observations if we disregard the ratios R derived for very young associations connected with large H II regions, like I Ori and NGC 2244. We shall discuss this point in more detail in Section 5 of this paper.

2. GALACTIC ROTATION

Let us first turn to galactic rotation. The most complete recent discussion is that of Feast and Shuttleworth (1965). Aware of a bias in the photometric distances, caused by a logarithmic error distribution, they applied a statistical correction to these distances (Figure 1).

The work of Feast and Shuttleworth is based on $R = 3·0$. A change to the more probable value $R = 3·2$ entails a second correction, which, for distances up to 5 kpc, is of about the same size as the first—see also Table 1. In evaluating the correction to r due to the change in R, I have taken the mean reddening of OB stars, Cepheids and open clusters as a function of distance shown in Figure 2, using data from Schmidt-Kaler (1958; cf. also Isserstedt and Schmidt-Kaler 1961, and, for OB stars of known radial velocity in the northern Milky Way, Bonneau 1964).

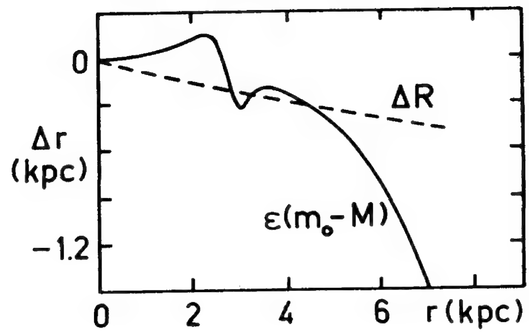

FIG. 1. Statistical corrections Δr to photometric distances r of B-type stars. The curve labelled ϵ $(m_0 - M)$ shows the correction due to logarithmic bias (Feast and Shuttleworth 1965, Figure 6); the other curve indicates corrections due to a change ΔR in the ratio R of visual extinction and reddening (cf. Table 1).

Table 1

Statistical corrections to photometric distances of B stars

Distance r (kpc)	Correction Δr (kpc) for logarithmic bias	for $\Delta R = +0{\cdot}2$
1	+ 0·04	− 0·07
2	+ 0·14	− 0·15
3	− 0·32	− 0·21
4	− 0·25	− 0·28
5	− 0·46	− 0·34
6	− 0·87	− 0·39

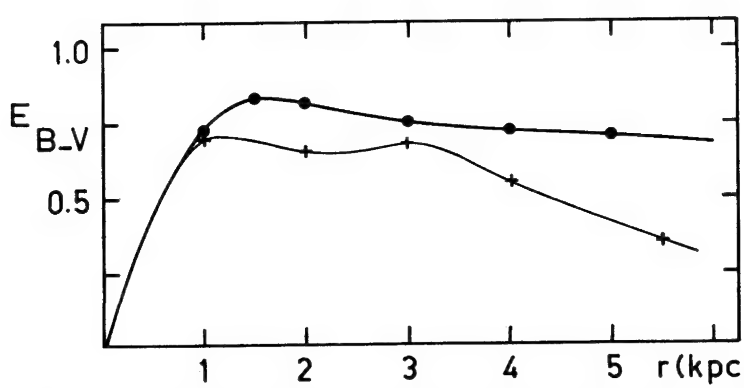

FIG. 2. Mean reddening of B stars as a function of distance (dots: Schmidt-Kaler, crosses: Bonneau).

Table 2

Mean rotation curve, amended from Feast and Shuttleworth (1965, Table IV)

Mean R (kpc)	Mean $(\omega - \omega_0)$ (km sec^{-1} kpc^{-1})
6·15	$+ 12{\cdot}72 \pm 1{\cdot}33$
6·98	$+ 8{\cdot}06 \pm 0{\cdot}91$
7·91	$+ 6{\cdot}96 \pm 0{\cdot}59$
8·83	$+ 3{\cdot}62 \pm 0{\cdot}28$
9·65	$+ 0{\cdot}68 \pm 0{\cdot}10$
10·26	$- 0{\cdot}83 \pm 0{\cdot}08$
11·44	$- 4{\cdot}54 \pm 0{\cdot}20$
12·15	$- 4{\cdot}96 \pm 0{\cdot}36$
13·00	$- 5{\cdot}09 \pm 0{\cdot}50$

From the corrections Δr in Table 1 I have derived corrections to the distances* from the galactic centre used by Feast and Shuttleworth; this leads to an amended version of their Table IV given here in Table 2.

The rotation curve of Feast and Shuttleworth (1965, Figure 7) compared rather well with the results of the earlier 21-cm line work. The big discrepancies between the optical and the radio-astronomical rotation curves noted by Bahng *et al.* (1957) and by Münch and Münch (1960) had disappeared, evidently as a result of the application of corrections for logarithmic bias. However, significant systematic differences from the Leiden curve (Kwee *et al.* 1954) remained. These led Feast and Shuttleworth to conclude that the Sydney rotation curve (Kerr 1962) and its extrapolation outside the solar circle appeared more accurate. Figure 3 shows the run of $\omega(R)$ obtained after correction for ΔR, together with the Leiden rotation curve and its extrapolation by Schmidt's (1956) model, and with the curve for model VII of Shane and Bieger-Smith (1966). The agreement with both curves is almost perfect. It is slightly poorer with the Sydney curve (not plotted). This disposes of theories of spiral structure involving systematic deviations between the galactic rotation of stars and gas exceeding, say, 6 km/sec.

As the best values of *Oort's constant* we find, from this revision of the work of Feast and Shuttleworth: $A = +\ 15{\cdot}2 \pm 0{\cdot}8$ km sec^{-1} kpc^{-1}, and from the discussion of open clusters by Johnson and Svolopoulos (1961): $A = +\ 15{\cdot}3$ km sec^{-1} kpc^{-1}.

It should be noted that there may be systematic errors up to 10 km/sec in the radial velocities, due to inclusion of double stars (Abt and Bautz 1963). Bonneau (1964) noted that the radial velocities of lower quality are systematically negative with respect to those of higher quality of an amount of the same order of magnitude.

Since 21-cm line velocities for early-type clusters have been found to agree with the optical velocities within 5 or 10 km/sec, it seems possible to extend the rotation curve farther out by means of a combination of photometric distances and 21-cm hydrogen velocities of open clusters. To do this high angular resolution will be necessary.

*In Table 2, in Figure 3, and in $\omega(R)$ the symbol R is used for the distance to the galactic centre; elsewhere in this paper it denotes the ratio of extinction to reddening.—*Editor.*

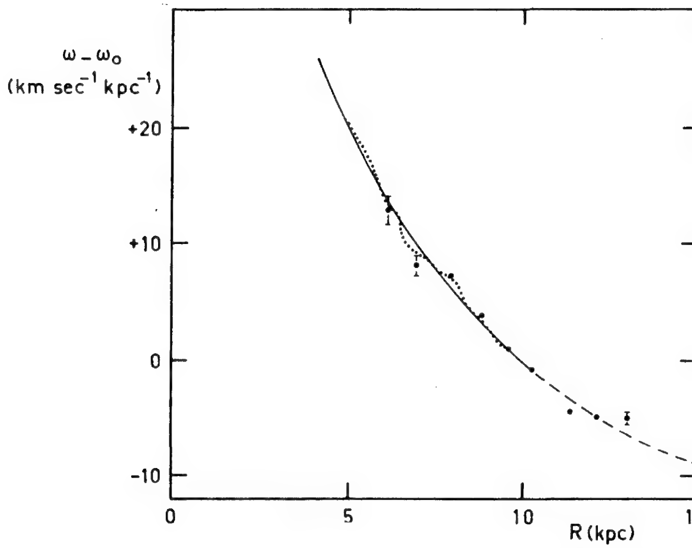

FIG. 3. Galactic rotation from B stars (amended from Feast and Shuttleworth, cf. Table 2). The error bars are twice the standard error. The smooth curve is the Leiden 21-cm rotation curve by Kwee, Muller and Westerhout (1954); the dashed extension is its extrapolation via a mass model by Schmidt (1956). The stippled curve represents model VII from Shane and Bieger-Smith (1966).

3. PECULIAR MOTIONS

With respect to peculiar motions I wish to make just one remark. There is plenty of evidence (for instance, Kraft and Schmidt 1963 from Cepheids) for local deviations from the mean rotation law, reaching 10 to 20 km/sec over regions of about 1 kpc in diameter. In order to bring the large concentrations of neutral hydrogen in coincidence with the main optical spiral features, deviations from circular motion of about 15 km/sec are needed (Schmidt-Kaler 1966).

4. SPIRAL STRUCTURE

The best spiral tracers are H II regions, early-type aggregates (O-B0) and open clusters (O-B2). I have recently summarized the available information (Schmidt-Kaler 1965, 1966).

5. THE RATIO OF EXTINCTION TO REDDENING

The photometric distances involved in the determination of spiral structure bring us back to the ratio of visual extinction to $B - V$ reddening. We have made two simple tests to decide between Johnson's wide range of values and a constant close to the classical value $R = 3{\cdot}0$.

(*a*) First we compare the distribution in the galactic plane of open clusters with earliest type O to B2 for the two cases (Figure 4). In the case $R = 3{\cdot}0$ (Figure 4a) three well-separated spiral features are visible, although the picture is confused in the quadrant

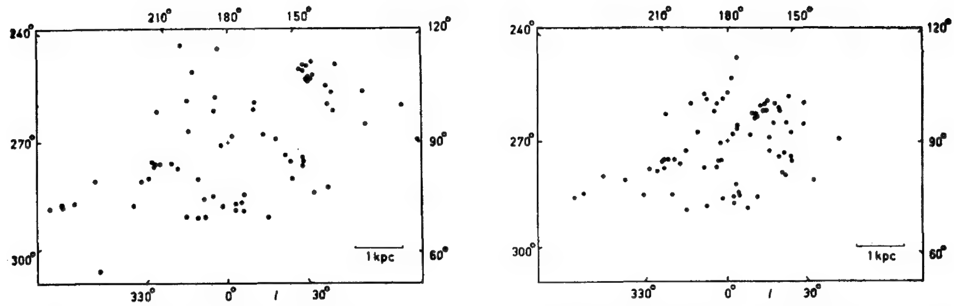

FIG. 4a. Distribution of early-type open clusters (O – B2), for R = 3·0. From Schmidt-Kaler (1965), supplemented by seven new objects.

FIG. 4b. Same as Figure 4a, for $R = R(l)$ taken from Johnson (1967, Figure 41).

l = 180° to 270°. Use of Johnson's (1967) final values $R = R(l)$ gives a picture (Figure 4b) which shows essentially no structure.

(*b*) Second we consider the correlation of the radial velocities of O-B5 stars and Cepheids with distance in the two cases (Figure 5). The B-star data have been taken from the catalogue of Rubin *et al.* (1962), the Cepheid data from Kraft and Schmidt (1963); only stars with $|b| < 13°$ and within 9°.5 of the longitudes l = 45°, 135°, 225° and 315° were used, so that the galactic-rotation effect should be not less than 90% of its maximum. The straight lines represent linear approximations of differential galactic rotation, based on independent data from open clusters, with A = + 15 km sec^{-1} kpc^{-1} (Johnson and Svolopoulos 1961) and A = + 20 km sec^{-1} kpc^{-1} (Johnson 1967), respectively. The zero was determined from the standard solar motion. Comparison of the correlations of velocity with distance in the two cases leads to four remarks:

(*i*) The scatter in the case of variable $R(l)$ is considerably greater than that for R = 3·0.

(*ii*) While in the latter case the velocities show an almost linear increase with distance, this is not true for the case of variable $R(l)$. For $r \geqslant$ 1·5 kpc the mean velocity is even constant.

(*iii*) The differential galactic rotation from open clusters is in perfect agreement with the individual B-star data for R = 3, while in the other case the open-clusters curve gives a crude representation at best.

(*iv*) Individual plots of the data for the four longitude intervals show that, for $r >$ 0·6 kpc, most of the $R(l)$ points lie on one side of the line A = + 20 km sec^{-1} kpc^{-1}. For R = 3, however, the distribution of the points around the straight line A = + 15 km sec^{-1} kpc^{-1} is very nearly symmetric, at least up to r = 2·5 kpc.

We conclude from these two tests that the most probable value for the ratio of extinction to reddening is R = 3·2, with regional variations of less than ± 0·5, in general. Johnson's results were based on three types of observations:

(1) geometric distance estimates from the diameters of open clusters as compared to photometric distance determinations;

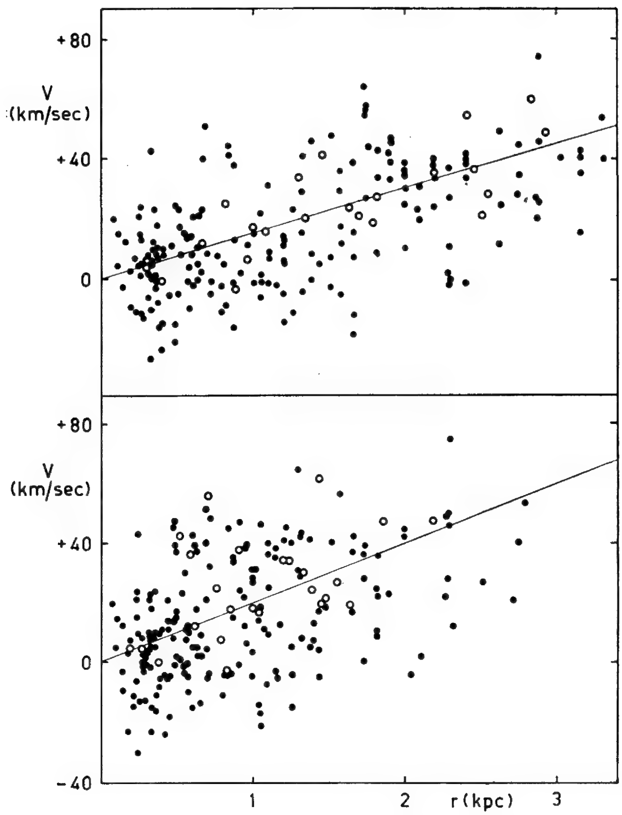

FIG. 5. Radial velocities of O–B5 stars (dots) and Cepheids (circles), reduced to the local standard of rest. Upper part: for $R = 3{\cdot}0$; lower part: for $R = R\,(l)$ taken from Johnson (1967, Figure 41).

(2) stars within a cluster or association with different amounts of extinction, from which $\Delta V/\Delta(B - V)$ may be determined;

(3) infrared measurements of individual stars.

Method (1) rests on the rather ill-defined apparent diameters of open clusters, and is, in the manner used by Johnson, open to criticism because of statistical bias. Method (2) has been discussed in detail by Becker (1966), with the result that no large deviations from $R = 3$ are warranted by the observational data. With respect to the third method an inspection of Johnson's data shows that the high values of R are always connected with a hump on the reddening curve near $\lambda^{-1} = 0{\cdot}2\ \mu^{-1}$. This is especially apparent when the reddening is small. This feature may be interpreted as free-free emission of a tenuous outer stellar envelope with a temperature around 10 000 °K. Evidence of such an envelope is known, e.g. for φ Per (which shows the feature in a striking manner) and for Of stars. If this suspicion is justified, the total interstellar extinction should be extrapolated from

measurements at $\lambda^{-1} > 0{\cdot}3\ \mu^{-1}$, i.e. not including the far infra-red. Doing this and excluding the Orion region we find values of R ranging from 3·0 to 3·6 and averaging 3·23.

This result permits us to use with some confidence the picture of galactic spiral structure presented earlier (Schmidt-Kaler 1965, 1966), which is confined to distances r smaller than 3 kpc.

6. CURRENT RESEARCH AT LARGER DISTANCES

To extend the optical picture beyond $r = 3$ kpc, we have research under way in two directions.

(1) Measurement of the OB stars of the Hamburg-Cleveland survey in *UBV* and partially in Hβ. In a joint program with Drs Bigay and Haug about 1400 stars have been measured so far.

(2) To obtain an optical picture of the spiral structure of the whole Galaxy, photometric distance estimates are not accurate enough. A spiral feature of 1 kpc width at a distance of 10 kpc will be completely smeared out, if the standard error of the distance modulus is greater than $\pm 0^m.07$. Therefore we have looked for features allowing geometric distance estimates. Indeed one of my students, Mr Isserstedt, has succeeded in finding one. We hope to be able to present the desired picture in the near future.

REFERENCES

Abt, H. A., Bautz, L. P. 1963, *Astrophys. J.*, **138**, 1002.

Bahng, J. D., Code, A. D., Whitford, A. E. 1957, *Sky Telesc.*, **16**, 529.

Becker, W. 1964, *Z. Astrophys.*, **58**, 202.

Becker, W. 1966, *Z. Astrophys.*, **64**, 77.

Becker, W., Fenkart, R. 1963, *Z. Astrophys.*, **56**, 257.

Bonneau, M. 1964, *J. Observateurs*, Marseille, **47**, 251 (also in 1965, *Ann. Obs. Besançon*, **6**, 63).

Borgman, J. 1966, *Trans. int. astr. Un.*, **12B**, 397.

Feast, M. W., Shuttleworth, M. 1965, *Mon. Not. R. astr. Soc.*, **130**, 245.

Isserstedt, J., Schmidt-Kaler, Th. 1964, *Z. Astrophys.*, **59**, 182.

Johnson, H. L. 1967, Interstellar Extinction, in Vol. VII of the series: *Stars and Stellar Systems*, Univ. of Chicago Press, Chicago.

Johnson, H. L., Borgman, J. 1963, *Bull. astr. Inst. Netherl.*, **17**, 115.

Johnson, H. L., Svolopoulos, S. N. 1961, *Astrophys. J.*, **134**, 868.

Kerr, F. J. 1962, *Mon. Not. R. astr. Soc.*, **123**, 327.

Kraft, R. P., Schmidt, M. 1963, *Astrophys. J.*, **137**, 249.

Kwee, K. K., Muller, C. A., Westerhout, G. 1954, *Bull. astr. Inst. Netherl.*, **12**, 211.

Münch, G., Münch, L. 1960, *Astrophys. J.*, **131**, 253.

Rubin, V. C., Burley, J., Kiasatpoor, A., Klock, B., Pease, G., Rutscheidt, E., Smith, G. 1962, *Astr. J.*, **67**, 491.

Schmidt, M. 1956, *Bull. astr. Inst. Netherl.*, **13**, 15.

Schmidt-Kaler, Th. 1958, *Z. Astrophys.*, **46**, 145.

Schmidt-Kaler, Th. 1961, *Astr. Nachr.*, **286**, 113.

Schmidt-Kaler, Th. 1965, in *Observational Aspects of Galactic Structure*, Eds. A. Blaauw and L. N. Mavridis, Chap. XII, Athens.

Schmidt-Kaler, Th. 1966, *Trans. int. astr. Un.*, **12B**, 416.

Shane, W. W., Bieger-Smith, G. P. 1966, *Bull. astr. Inst. Netherl.*, **18**, 263.

Sharpless, S. L., Osterbrock, D. E. 1952, *Astrophys. J.*, **115**, 89.

Whitford, A. E. 1958, *Astr. J.*, **63**, 201.

Discussion

T. K. Menon: The reality or otherwise of spiral structure in galaxies can best be judged from Courtès' narrow-band photographs of external galaxies.

D. Lynden-Bell: I should like to ask Professor Oort how long it will be before we have a geometrical measurement of R_0 by determining A from proper motions. At least this would avoid the uncertainties involved in other methods of distance measurement.

J. H. Oort: Do you mean: how many centuries?

At the present time proper motions of population-I stars can at the very best tell us something about distances up to 1000 pc. For the spiral problem we have to go out considerably further. It will be quite a long time before one can hope to do this successfully.

M. Schmidt: I should hope that a mainly geometrical determination of R_0 from population-I objects with zero radial velocity might yield results. The distances of such objects could probably be determined reliably, because their local counterparts (at the *same* distance from the galactic centre, and therefore presumably similar as regards chemical abundances and physical properties) are or can be well calibrated.

Oort: But you are still faced with the difficulty of the systematic deviations from circular motion.

Schmidt: For a major improvement of R_0, one would need a very large number of objects.

Oort: Many objects, and in different parts of the sky.

Th. Schmidt-Kaler: It may interest Lynden-Bell that Dieckvoss and de Vegt at Hamburg and Van Schewick at Bonn have projects underway to determine absolute proper motions of open clusters on the system of the FK4. The reference stars are tied into the AGK3R-system and GC-system, respectively, which in turn are tied into the FK4-system.

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26. THE PARKES SURVEY OF 21-CM LINE EMISSION NEAR THE GALACTIC EQUATOR

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ABSTRACT

A detailed 21-cm survey of the Milky Way in the longitude range 185° to 63° is described, and the objectives discussed. A preliminary study of some symmetry properties indicates that the line profile integrals, taken over velocities corresponding to locations outside the solar circle, are systematically higher on the southern-longitude ($l^{\mathrm{II}} < 360°$) side of the galactic centre.

An extensive survey of 21-cm line radiation from the Milky Way strip has been carried out with the Parkes 210-foot (64-m) telescope and multichannel receiver. The beamwidth is 14 minutes of arc and the bandwidth for the large-scale survey 36 kHz = 7·6 km/sec. Detailed observations have been made for several years in the longitude range 300° to 63° (Kerr), with a more recent extension to include the range 185° to 300° (Hindman). The observations have generally been taken along lines of constant latitude or longitude, with profiles recorded every six minutes of arc. The data have all been reduced, and about half are in publishable form.

A considerable amount of fine structure appears in the detailed diagrams, but this has not yet received close attention. A synoptic view of the larger-scale features can be obtained from a set of contour diagrams in the velocity-longitude plane, which were drawn from observations at 1° intervals. These diagrams will be published shortly in the *Australian Journal of Physics*. They were all shown at the Symposium, and the major structural features discussed.

The ultimate objective of this survey is an improved and more detailed picture of the distribution and velocity field of the neutral hydrogen. The fine-structure details will have to be studied individually, but first it is necessary to consider the large-scale phenomena in order to derive a distance scale. We hope that an overall solution to the kinematic problem can be found by taking into account the observations over the whole galactic disk, and using the whole of each profile, rather than just the data for the tangential points as has been done before.

One useful preliminary step is to study the symmetry properties of the hydrogen distribution, for example through the integrated brightness, B_{int}, i.e. the integral under the line profile. The variation of B_{int} with longitude around the galactic equator is shown in Figure 1. Comparison of the results on opposite sides of the galactic-centre direction indicates that B_{int} is higher on the southern side ($l^{\mathrm{II}} < 360°$) over most of the comparison range. Further information can be obtained by considering the integrals for positive and negative velocities separately. We find that the integrals corresponding to gas in the inner

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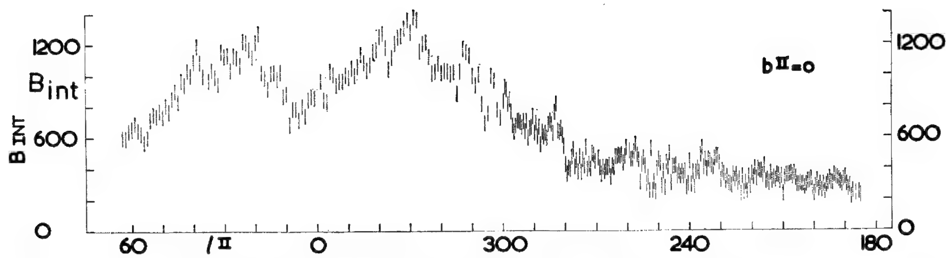

FIG. 1. 21-cm integrated brightness along the galactic equator. The unit is $3{\cdot}5 \times 10^{-17}$ W m^{-2} sr^{-1}. The height of each vertical line indicates the estimated probable error.

regions of the Galaxy (positive velocities for northern longitudes, $l^{II} > 0°$, and negative velocities for southern longitudes) are about the same on the two sides of the system. On the other hand, for outer-region gas the integrals are systematically larger on the southern side than they are on the northern.

Overall comparisons of various kinds will put limits on the types of model that can be tried in a general solution for the density and velocity distributions of the gas.

Discussion

B. F. Burke: Kerr's observation that the integrated hydrogen brightness, B_{int}, is greater at the southern longitudes than at the northern, for hydrogen with velocities corresponding to distances R greater than R_0, may be related to his comment that the velocity range observed at the northern longitudes is narrower. For equal amounts of hydrogen, a narrower velocity range would imply greater optical depth, and greater self-absorption, leading to a smaller value of B_{int}; so perhaps the amount of hydrogen is not necessarily different in the two longitude intervals.

F. J. Kerr: This effect must certainly be present, but it is not large enough to account for the observed difference.

G. W. Rougoor: From the Kootwijk and old Australian surveys I find that the total amounts of hydrogen in the Galaxy, integrated over all longitudes, are equal within 2% for negative and positive velocities. If we take positive and negative velocities together, the integral over longitudes 0° to 180° is within a few per cent of that over longitudes 180° to 360°.

Kerr: It is dangerous to use the old surveys, in which different systems were employed. The advantage of the recent results described by me is that both sides of the centre have been covered with the same equipment and the same techniques.

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27. VARIATION OF THE AMOUNT OF HYDROGEN ALONG THE GALACTIC RIDGE

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ABSTRACT

The integral N_H of neutral-hydrogen density along the line of sight is determined from the Kootwijk and Sydney surveys. The run of N_H with galactic longitude agrees well with that of thermal continuous radiation and that of the optical surface brightness of the Milky Way.

A few years ago I determined hydrogen-profile integrals similar to those described by Kerr in Paper 26, but on the basis of the Kootwijk and Sydney observations (Muller and Westerhout 1957; Kerr *et al.* 1959). From the integrated brightness B_{int}, or from $\int T_b dV$, one can directly derive N_H, the number of neutral hydrogen atoms summed up over a column of 1 cm^2 cross-section, provided the optical depths are small*. In Figure 1, the thick curve shows N_H, thus derived, as a function of galactic longitude. A number of maxima are in evidence, superposed on the expected general increase as the line of sight approaches the galactic centre.

We can take the effects of optical depth into account in a very rough manner by considering T_{max}/T_{kin} for each profile and assuming, as a first approximation to the complex profile shapes, a dispersion profile. In the curve joining the corrected values of N_H (thin curve in Figure 1) all maxima are enhanced but no new maxima appear. I have also integrated the numbers of hydrogen atoms per cm^3 according to the classical work by Van de Hulst, Muller and Oort (1954) and by Schmidt (1957); the results are shown for comparison. This curve is, however, based on certain assumptions regarding the velocity dispersion of the clouds.

The arrows indicate the directions of those maxima in the surface brightness of the Milky Way which are certainly not due to absorption features or to lack of absorbing matter.† Good general agreement is apparent; this suggests that the centres of optical and 21-cm spiral features coincide within about 100 pc. Again, the distribution of the thermal radiation according to Moran (1965) shows a very similar picture.

Finally I wish to point out that the N_H-method of locating spiral structure is superior near the tangential points, where the conventional method breaks down. Moreover, the

*The relationship is as follows: for infinitely small optical depth, $B_{int} = 3{\cdot}5 \times 10^{-17}$ W m^{-2} sr^{-1}, the unit used by Kerr in Paper 26, corresponds to $N_H = 0{\cdot}2172 \times 10^{20}$ cm^{-2} = $7{\cdot}04$ cm^{-3} pc. —*Editor.*

†Recently, Behr (1966) has criticized Elsässer's intuitive interpretation of the surface photometry of the Milky Way, as well as mine, which took into account the effect of interstellar absorption within about 2 kpc. Behr's models are, however, based on the assumption that the thickness of the absorbing layer is equal to that of the galactic disk responsible for the general luminosity near the plane and for its increase towards the centre.

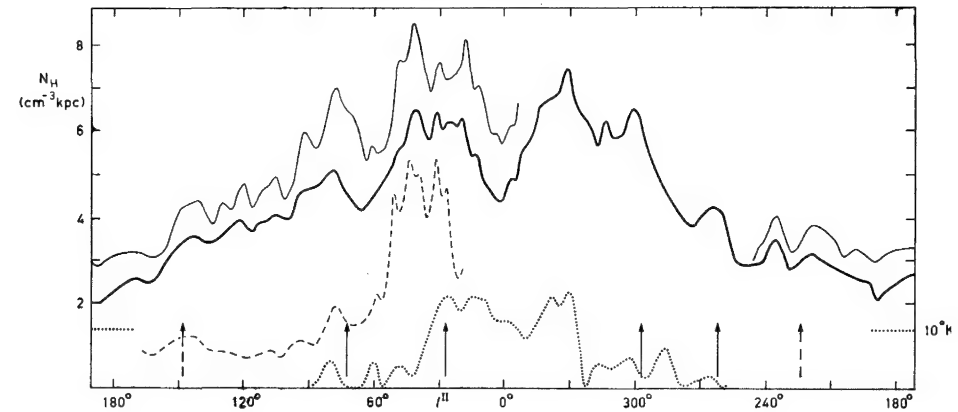

FIG. 1. Surface density of hydrogen as a function of galactic longitude, for positions along the galactic ridge (the maximum deviation from the galactic equator is ± 2°5). The quantity N_H, the number of neutral hydrogen atoms in a column of 1 cm² cross-section, was determined from the Kootwijk and Sydney profiles. The thick line gives N_H for the assumption of small optical depth; the thin line gives N_H after correction for optical depth, by means of an approximation of the actual profiles by dispersion profiles. The dashed curve gives N_H as found from the density distributions determined by Van de Hulst, Muller and Oort (1954) and Schmidt (1957); the scale for this curve is reduced by a factor of 3. The dotted curve at the bottom shows the distribution of thermal radiation according to Moran (1965). The arrows indicate the locations of those maxima of the surface brightness of the Milky Way (in the blue and yellow) which are certainly not due to effects of local interstellar absorption (Isserstedt and Schmidt-Kaler 1964).The ratio between Sydney and Kootwijk temperatures was found to be 1.32.

assumption that the nearby gas is at higher, the distant gas at lower latitudes, an assumption which is usually made to resolve the basic distance ambiguity, is by no means confirmed by the apparent flatness of the hydrogen layer in the inner parts of the Galaxy, because of the circular reasoning involved. At present, I am analyzing new profiles obtained recently with the Bonn 25-m dish and spaced 0°5 along the galactic equator, with this method supplemented by Gaussian analysis. Starting from the well-known local arm I work inward, separating step by step the velocity ranges responsible for the successive maxima.

REFERENCES

Behr, A. 1966, *Z. Astrophys.*, **62**, 157.
Isserstedt, J., Schmidt-Kaler, Th. 1964, *Z. Astrophys.*, **59**, 182.
Kerr, F. J., Hindman, J. V., Gum, C. S. 1959, *Austr. J. Phys.*, **12**, 270.
Moran, M. 1965, *Mon. Not. R. astr. Soc.*, **129**, 447.
Muller, C. A., Westerhout, G. 1957, *Bull. astr. Inst. Netherl.*, **13**, 151.
Schmidt, M. 1957, *Bull. astr. Inst. Netherl.*, **13**, 247.
Van de Hulst, H. C., Muller, C. A., Oort, J. H. 1954, *Bull. astr. Inst. Netherl.*, **12**, 117.

I.A.U. Symposium no. 31, 1967

28. THE MARYLAND-GREEN BANK GALACTIC 21-CM LINE SURVEY

GART WESTERHOUT

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ABSTRACT

A strip of 2° width along the galactic equator is being surveyed with an angular resolution of 0°.2 and velocity resolution of 2 km/sec.

The 300-foot (91-m) transit radio telescope at the National Radio Astronomy Observatory in Green Bank, West Virginia, which is the largest paraboloid in the world suitable for measurements of the 21-cm line, is being used for a detailed survey of neutral hydrogen in the Galaxy. Since the telescope has a beamwidth of 10 minutes of arc, the angular resolution of the survey is about ten times better than that of the previous large-scale surveys made in Leiden and Sydney some ten years ago.

The *main body of the survey* will consist of line profiles, spaced at 1/2 beamwidth (6′ arc) or less along the galactic equator between longitudes 11° and 235°. Initially, the latitude coverage will be from −1° to +1° only; it is intended to widen this range later. The material now at hand was obtained in 650 observing hours between 22 October 1964 and 30 September 1965.

During this first year, the aim was to observe the galactic-equator strip once, at intervals of 12′ in declination. Due to lack of observing time we did not quite succeed, and some gaps are left here and there, although a region around $l = 120°$ is already almost entirely covered at 6′ intervals. The observations were made in the form of drift scans at constant declination, between right-ascension limits chosen to fit the latitude range, −1° to +1°, selected. Along every track, at least two scans were made in order to fully cover the frequency range of interest; between $l = 11°$ and 80°, three scans were necessary for this. In most cases, no repeat scans are available. The spacing in declination, at present 12′, will later be decreased to 6′. Thus, we have finished about 60% of a complete survey, if 'complete' is meant to indicate single coverage at 6′ intervals.

The observations in the galactic-equator strip have been supplemented by profiles taken in two other programs. (1) Approximately 50 selected regions, each about 1° × 2° in size and lying close to the galactic plane, were measured at intervals of 5′ in declination; this material is being used for a survey of neutral hydrogen associated with galactic clusters (Howard and Westerhout 1965). (2) About 20 selected regions similar to those under (1) have been observed in a survey of neutral hydrogen associated with H II regions (Riegel 1966, 1967).

The *receiver* is the NRAO 100-channel autocorrelation receiver. It provides a 100-point autocorrelation function of the signal in one of four bands, respectively 2500 kHz, 625 kHz, 250 kHz and 62·5 kHz wide. After Fourier transformation in an electronic computer, and application of certain corrections, an 85-point power spectrum is obtained.

The effective bandwidth used for this survey was 7 kHz = 1·5 km/sec, the frequency coverage about 500 kHz (100 km/sec). Some smoothing operations were performed to improve the signal-to-noise ratio. The *characteristics of the contour maps*, an example of which is given in Figure 1, are as follows:

Bandwidth: 2 km/s half-power width; the shape of the passband is approximately Gaussian, with 4% negative sidelobes at 2 km/s on either side of the center of the band.

Beamwidth: $12\rlap{.}'5$ (arc) = 50 $(\cos \delta)^{-1}$ seconds of time in right ascension; 10′ (arc) in declination.

Intensity scale: One contour unit is $5 \pm 0{\cdot}4$ °K of antenna temperature; internal consistency better than ±5%.

Noise: The r.m.s. noise is a function of receiver temperature (varying from 200 °K to 350 °K) and declination (effective integration time 42 $(\cos \delta)^{-1}$ seconds). For the best contour maps r.m.s. noise is 0.5 °K, for the poorest it is about 2 °K, so that peak-to-peak noise fluctuations vary between 2·5 and 10 °K in T_a (1/2 to 2 contour units). During the next observing period, the scans with high r.m.s. noise will be re-observed, and the maps replaced by better-quality maps.

Conversion of antenna temperature into brightness temperature is complicated. The antenna pattern contains, in addition to the main beam, which is 10′ (arc) wide, a component ('error beam') of $2\rlap{.}^\circ 5$ width, due to deviations of the antenna surface from a perfect paraboloid. Moreover, the antenna efficiency decreases with altitude owing to dish deformations. When the survey is complete, corrections for the error pattern and for the dish deformation will be applied to all profiles, in one overall de-smoothing operation. For rough calculation, one might use the following rules:

$\overline{T}_b = 1{\cdot}8\, T_a$ (or 1 contour unit = 9 °K in T_b) for regions of size approximately equal to the main beam;

$\overline{T}_b = 1{\cdot}1\, T_a$ (or 1 contour unit = 5·5 °K in T_b) for regions approximately 3° in size or larger.

These values are to be multiplied by a factor varying from 1·24 at declination −20° to 1·00 at declinations above +15° (within 5%).

Contour maps of the type of Figure 1, giving line intensity as a function of radial velocity and right ascension, were produced for each scan by the IBM 7094 computer at Maryland. The contours were plotted in the form of numbers from 0 to 9, returning to 0 at intensities of 10 and 20 units. The accurate position coordinates of each line are shown in the right- and left-hand columns; from left to right: right ascension and declination (1950), l and b. These quantities and the contour numbers can be read, if needed, with the aid of a magnifier.

A total of 805 contour maps are now available from the author (Westerhout 1966); they were distributed to participants in the Symposium. Also available are the line profiles used for these maps, on magnetic tape, sorted by declination and right ascension. When the survey is complete, the data will be re-sorted by l and b, and new contour maps will be provided giving intensity as a function of galactic latitude and velocity, and of longitude and velocity.

To conclude, I would like to point out some *features* which are obvious after a first inspection of the contour maps.

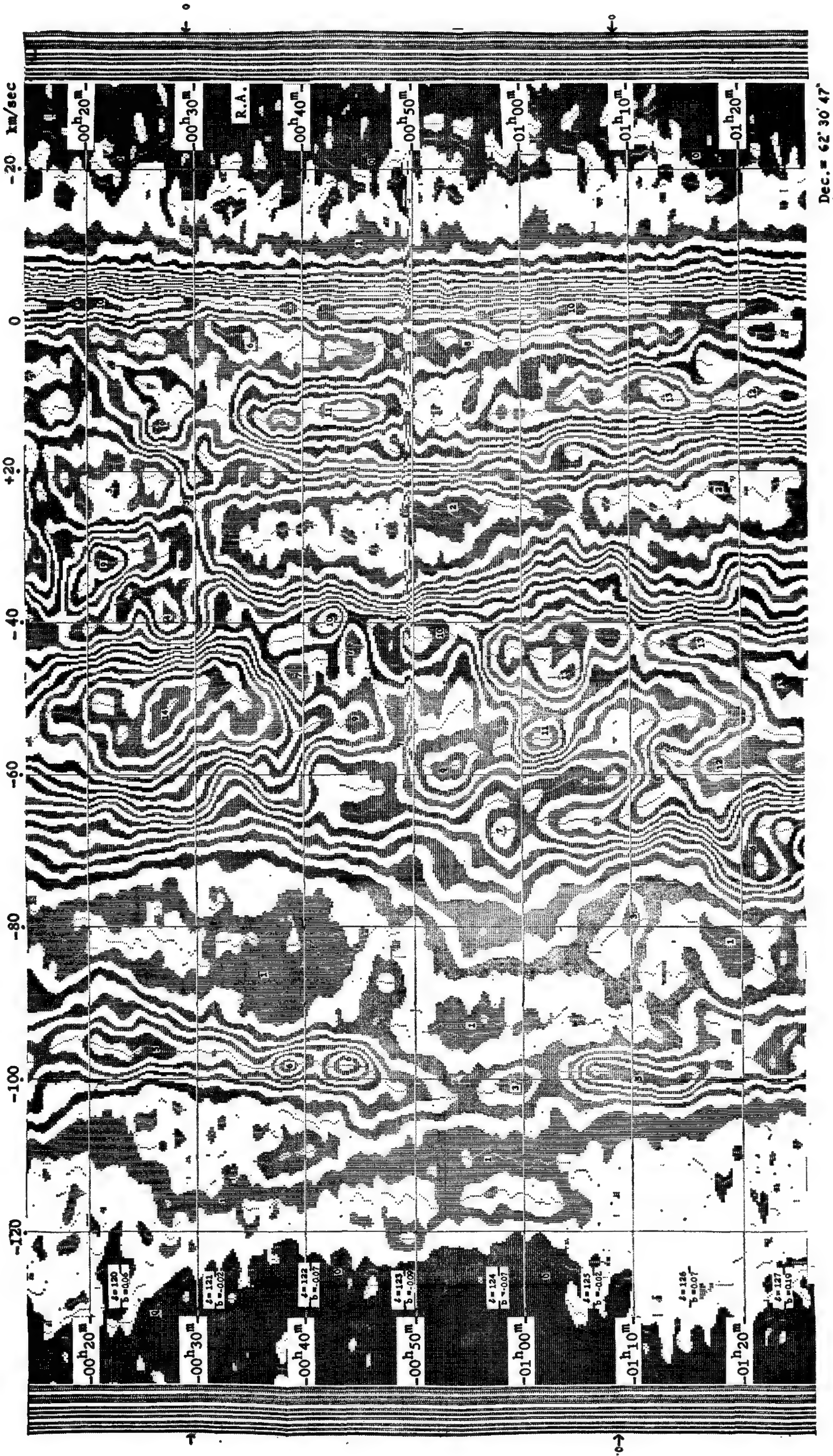

FIG. 1. Computer-produced contour map of the 21-cm line radiation at declination 62° 30′ 47″, between right ascension $00^h\ 15^m$ and $01^h\ 25^m$, approximately along the galactic equator (within ± 0°.2) between l = 119° and 127°. Radial velocities with respect to the local standard of rest are given at the top. The contour intervals are 5 °K in T_a.

It looks as though there are three main types of hydrogen concentrations, distinguished by their size. First, there are the *large concentrations*, typically between 500 and 1000 pc in size. The spiral arms appear to be made up of these concentrations, rather than being continuous entities; or else, these large concentrations occur in a smoother spiral-arm medium. Second, *cloud complexes* are of the order of 100 pc, often superimposed on the larger concentrations and sometimes, but not always, showing internal structure. Third, there are the individual *clouds*, small objects less than 10 pc in size.

One striking point is that the spiral arms seem to be better outlined by the *inter-arm regions*, which are relatively smooth and where intensities often are very low: intensity ratios arm/inter-arm go as high as 10. And finally, the detailed cross-sections in the region between $l = 11°$ and $70°$ show that often it will be hard to decide which is the 'tangential velocity'. In many cases, there are differences in the *terminal velocities* of up to 5 km/sec, within an interval of one or two degrees in galactic latitude around $b = 0°$, which would be fairly well smoothed out by a wider beam. It is clear that a very large body of material is available in these data; the author hopes to use them for a new derivation of the large-scale velocity and density distribution of the neutral hydrogen in our Galaxy.

This investigation was supported by grants from the National Science Foundation.

REFERENCES

Howard, W. E., Westerhout, G. 1965, *Astr. J.*, **70**, 679.

Riegel, K. W. 1966, 21-cm Line Observations of Small-Diameter Galactic H II Regions, Thesis, University of Maryland.

Riegel, K. W. 1967, *Astrophys. J.*, **148**, 87.

Westerhout, G. 1966, Maryland-Green Bank Galactic 21-cm Line Survey, first edition, University of Maryland, College Park, Maryland, U.S.A.

I.A.U. Symposium no. 31, 1967

29. PROGRESS REPORT ON 21-CM OBSERVATIONS AT LOW LATITUDE BETWEEN LONGITUDES (l^{II}) 0° AND 66°

W. W. Shane

(*Sterrewacht, Leiden, Nederland*)

In the course of several 21-cm observing programmes being carried out by the Leiden Observatory with the 25-meter telescope at Dwingeloo, a fairly complete, though inhomogeneous, survey of the region $l^{\text{II}} = 0°$ to 66° at low galactic latitudes is becoming available. The essential data on this survey are presented in Table 1. Oort (1967) has given a preliminary report on the first and third investigations. The third is discussed briefly by Kerr in his introductory lecture on the galactic centre region (Paper 42). Burton (1966) has published provisional results of the fifth investigation, and I have discussed the sixth in Paper 19. All of the observations listed in the table have been completed, but we plan to extend investigation 3 to a much finer grid of positions.

I wish to report here some preliminary results of investigations 4 and 5, which are devoted to studies of the regions in which the Scutum and northern Sagittarius Arms, respectively, are seen tangentially. Burton (1966) has been able to isolate a strong 21-cm feature, which he identifies with the Sagittarius Arm. A somewhat weaker, but still prominent, feature observed at the longitude at which the Sagittarius Arm is seen tangentially, and having a velocity higher than that of the arm, is interpreted by him as a gas stream with a velocity in the direction of galactic rotation about 7 km/sec in excess of that expected on the basis of a smooth rotation curve.

With the 140-foot (43-metre) telescope at Green Bank, Burton has recently measured the absorption spectrum of the continuum source W51, which is seen through the Sagittarius Arm near its tangent longitude. These unpublished observations have confirmed the reality of this separate high-velocity feature; it is the stronger of the two in the absorption profiles, which indicates that its temperature is much lower than that of the arm proper.

The Scutum Arm is known to be much broader and more diffuse than the Sagittarius Arm, and the results of the analysis are correspondingly less certain. The arm appears, on preliminary analysis, to be composed of several fragments, and there is some indication of the existence of a high-velocity stream similar to that found by Burton.

The tilts and locations of the arms can be estimated. The angles between the axes of the arms and the galactic radii are 81° and 78°, with an uncertainty of about 2°, for the Sagittarius and Scutum Arms respectively. The longitudes at which the arms are seen tangentially are 52° for the Sagittarius Arm and 33° to 38° for the various fragments of the Scutum Arm.

A striking feature of these observations is the apparent existence of a smooth envelope of neutral hydrogen surrounding the spiral structure. Such a phenomenon was already indicated by a preliminary examination of this material (Oort 1962). A similar suggestion, based on other observations, has been made by Takakubo (1963, 1967). Lindblad (1964) has suggested that the observed phenomena may be due to the presence of a body of

Table 1

Current Leiden 21-cm line investigations of the inner parts of the Galaxy

No.	Area investigated l^{II}	b^{II}	Grid $\Delta l \times \Delta b$	Velocity range (km/sec)	Bandwidth (km/sec)	Investigator
1	−10° / −15 } to − 4°	+ 1° / + 7 } to + 7°	1°.0 × 1°.0	− 50 to +150	3·4	P. Cugnon
2	+ 6 to +20 −10 to +20	−15 to − 7 + 7 to +15	2·0 × 2·0	−300 to +300	10·6	P. Cugnon
3	+ 2 / − 4 } to +20	− 5 / + 5 } to + 5	2·0 × 2·0	−250 to +350	3·4	W. W. Shane
4	+22 to +42	− 6 to + 6	1·0 × 0·5	0 to +170	3·4	W. W. Shane
5	+43·5 to +55·5 +43·0 to +57·0	− 4·5 to + 4·5 − 1·5 to + 1·5	1·5 × 1·0 0·5 × 0·5	0 to +100	1·7	W. B. Burton
6	+56 to +66 +58 to +64	− 5 to + 5 − 3 to + 3	1·0 × 1·0 0·5 × 0·5	−100 to +100	1·7	P. Katgert

neutral hydrogen whose kinematic properties resemble those of main-sequence stars of types A to F or of G-type giants. The more refined analysis of the Leiden observations now in progress indicates that the thickness of this hydrogen layer is about 500 pc and that it may contain about 10% of the neutral hydrogen in the region of the Galaxy in which it is observed.

REFERENCES

Burton, W. B. 1966, *Bull. astr. Inst. Netherl.*, **18**, 247.
Lindblad, P. O. 1964, *Pop. astr. Tidskrift*, **45**, 155.
Oort, J. H. 1962, in *The Distribution and Motion of Interstellar Matter in Galaxies*, Ed. L. Woltjer, W. A. Benjamin, Inc., New York, p. 71.
Oort, J. H. 1967, IAU Symposium no. 29 (in press).
Takakubo, K. 1963, *Sci. Rep. Tôhoku Univ.*, Ser. I, **47**, 65; *Sendai astr. Rap.* no. 85.
Takakubo, K. 1967, *Bull. astr. Inst. Netherl.*, **19**, 125.

Discussion

C. E. Heiles: Could the shape of the velocity-latitude contour plots be caused by optical-depth effects, together with a systematic variation of gas temperature with latitude?

W. W. Shane: I was referring to the shape of the outermost contours, at a brightness temperature of only a few degrees, so one would not expect to encounter saturation effects.

F. J. Kerr: The more widespread component is evident over a large range of longitude, but is in general less spread in latitude on the southern side of the galactic centre (i.e., at $270° < l < 360°$) than it is on the northern (at $0° < l < 90°$).

G. Westerhout: At the University of Virginia, F. Bash has noted (unpublished) that the model profiles by W. W. Shane and G. P. Bieger-Smith (1966, *Bull. astr. Inst. Netherl.*, **18**, 263) very often do not fit their observed profiles. This may give rise to errors in the rotational velocities of as much as 5 km/s. In many cases the cause of the poor fit appears to be that the profiles are saturated, and the kinetic gas temperature, T_g, is lower than the 130 °K adopted in their models. Obviously, T_g is a very important parameter and cannot be left out in discussions of velocities, velocity dispersions and densities of the neutral hydrogen.

Shane: The kinetic temperature is one of several parameters which might have been included in the model. Another is the velocity dispersion σ. We had to assume values for T_g and σ because the observational material was insufficient to determine so many free parameters simultaneously. One of the most important causes of the poor fit of the model to some of the observed line profiles is the assumption that the hydrogen density and velocity depend only on distance from the centre. This is unquestionably a very unsatisfactory assumption, even over the relatively short arcs considered, but any other assumption would again have introduced too much freedom into the model. The subject of the kinetic temperature and its distribution is certainly one which deserves the closest attention, but an error figure of 5 km/s as quoted by you seems to me surprisingly large.

K. Takakubo: From a survey of 21-cm profiles at intermediate galactic latitudes, I find for the wide Gaussian components ($\langle \sigma \rangle = 12{\cdot}7$ km/s) an average distance from the galactic plane, $\langle |z| \rangle = 180$ pc, using $A = +15$ km s^{-1} kpc^{-1}. The corresponding thickness of the gas layer agrees well with that found by Shane between 22° and 42° longitude. This indicates that the Orion Arm as well as the inner spiral arms discussed by Shane are surrounded by tenuous layers of neutral-hydrogen gas with large internal motions. For further details, see *Bull. astr. Inst. Netherl.*, **19**, 125. (These remarks were made in the general discussion concluding Part II of the Symposium.—*Editor.*)

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30. THE RUN OF TERMINAL VELOCITIES FOR THE WESTERN PART OF THE GALAXY

E. Bajaja, S. L. Garzoli, F. Strauss and C. M. Varsavsky
(Instituto Argentino de Radioastronomía, Villa Elisa, FCGR, Argentina)

ABSTRACT

The rotation curve observed with the Argentine radio telescope is systematically higher than that found at Parkes. The discrepancy appears to be caused by the difference in frequency resolution of the two receivers.

In a recent paper, Shane and Bieger-Smith (1966) have presented a rotation curve for the inner part of the Galaxy derived from fifty profiles obtained at positions along the galactic equator in the quadrant east of the galactic centre (that is, at $0° < l < 90°$). In their paper they show the curves obtained by Kerr (1967) for both quadrants, and a reasonably good fit between the Dutch and Australian data is observed. In this communication we present a rotation curve for the western quadrant ($270° < l < 360°$), based on ninety-one profiles taken at positions with $b = 0°$ and $291° \leqslant l \leqslant 337°$.

The observations were obtained with the 30-metre dish of the Villa Elisa station, which is jointly operated by the Carnegie Institution of Washington and the Instituto Argentino de Radioastronomía. The receiver has 56 channels, each 10 kHz = 2·1 km/sec wide. One complete profile consists of 112 points separated in frequency by 9 kHz. All points in the sky were observed twice, and reduced independently by the different authors; when two determinations of a velocity differed by 1·5 km/sec or more the point in question was observed again; a fourth observation was never necessary.

The terminal velocities were computed following the procedure suggested by Kerr (1964), that is, we identified the terminal velocity with that corresponding to a point in the profile halfway between the baseline and the peak with highest velocity. This does not correspond to the true rotational velocity but it gives a set of consistent results that can be compared with those of Kerr (1967), obtained at Parkes with a 64-metre paraboloid and 7·5 km/sec receiver bandwidth.

Figure 1 shows a superposition of our points on Kerr's curve. It must be kept in mind that both the angular and the frequency resolutions of the Parkes and Villa Elisa telescopes are quite different. Nevertheless the agreement is excellent over most of the curve, although a systematic discrepancy can be observed.

With the exception of two points, all the major differences are in the sense that higher velocities are observed at Villa Elisa. This, we believe, is due to the higher frequency resolution of the Argentine receiver. Indeed, if very little hydrogen is present at the tangential point, a low-intensity peak will appear as a shoulder on the side of the high peak produced by denser hydrogen away from the tangential point. If the frequency resolution is poor, the low-intensity shoulder will be lost in the main peak, and the mid-point in the profile will be taken at a lower velocity. This effect is illustrated by Figure 2, which shows the profile for $l = 308°$ ($R = 7·88$ kpc). If the shoulder B is smoothed out by

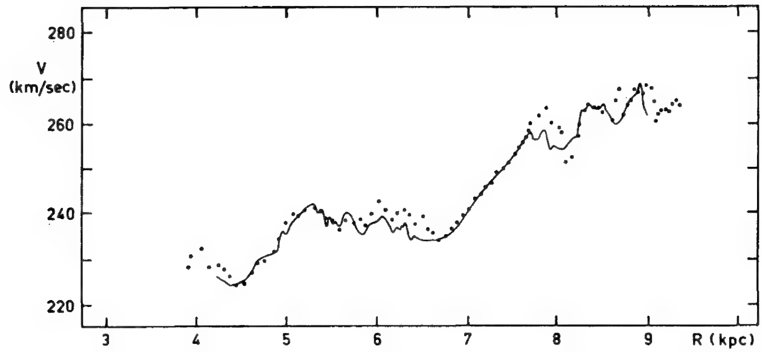

FIG. 1. The run of terminal velocities for $b = 0°$, $291° \leqslant l \leqslant 337°$. The full line is the curve obtained by Kerr (1967). The dots represent the observations described in this paper.

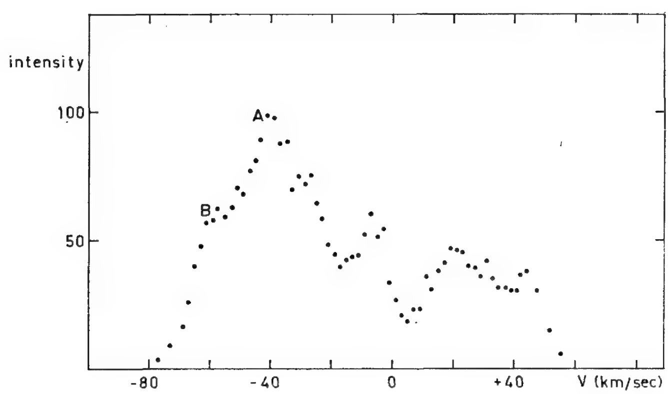

FIG. 2. The profile for $b = 0°$, $l = 308°$, as observed at Villa Elisa. The intensity is in arbitrary units (each unit corresponds approximately to 0·85 °K).

the width of the channels, the terminal velocity will be taken at an intensity halfway between A and the baseline. Such velocity will be lower than the one corresponding to the midpoint between B and the baseline. We believe that this effect is responsible for practically all the discrepancies found between the Australian and Argentine results, and that it shows the advantage of using relatively narrow channels.

A more thorough discussion of the results presented here, as well as rotation curves up to 100 pc above and below the plane, will be published elsewhere.

REFERENCES

Kerr, F. J. 1964, IAU Symposium no. 20, *The Galaxy and the Magellanic Clouds*, Eds. F. J. Kerr and A. W. Rodgers, p. 81, Austr. Acad. Sci., Canberra, Australia.
Kerr, F. J. 1967, *Austr. J. Phys.* (in press).
Shane, W. W., Bieger-Smith, G. P. 1966, *Bull. astr. Inst. Netherl.*, **18**, 263.

Discussion

H. van Woerden: When will Parkes get a narrow-band receiver?

B. J. Robinson: Plans are well advanced to equip the Parkes telescope with an adequate number of narrow-band filters. 60 filters of 10 kHz bandwidth will be installed shortly. A further 60 filters of 1 kHz bandwidth are on order, and should be ready in mid-1967. We should then have a frequency resolution that matches the angular resolution of the telescope. This is very necessary for a proper investigation of OH emission and absorption, and of H absorption.

B. J. Bok: You should have asked: When is Dwingeloo going to have a bigger dish?

Van Woerden: We are getting twelve small dishes instead.

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Chapter II B

Neutral Hydrogen in Galaxies

CHAIRMAN: R. L. Minkowski

(*Radio Astronomy Laboratory, University of California, Berkeley, Calif., U.S.A.*)

'This so-called ring is more like a disk with a hole in the middle. This is not that I disagree with the nomenclature. I just want to make sure that theoreticians do not get to think of . . . rings.'

B. F. Burke, in the Discussion (Paper 35)

31. COMPARISON OF THE DISTRIBUTION AND MOTION OF ATOMIC HYDROGEN IN OUR OWN GALAXY AND IN OTHER SPIRAL SYSTEMS

(Introductory Report)

B. F. BURKE

(*Department of Physics and Research Laboratory of Electronics**, *Massachusetts Institute of Technology, Cambridge, Massachusetts, U.S.A.*)

Our own stellar system has been studied in some detail by the Leiden and Sydney groups, whose maps of the large-scale hydrogen distribution are well-known; these are discussed by Lindblad in Paper 24 of this Symposium volume. The distances in our Galaxy are sufficiently small to reveal significant structure on the order of size of spiral arms, but the lack of a direct distance scale, with an indirect scale to be inferred from velocity models, is a serious handicap in reaching definite conclusions about the symmetry, number of spiral features, and inclination of spiral arms. In fact it is very difficult to decide whether the gas arms coincide with the spiral arms as defined by stars. By the study of external galaxies one can remove the scale uncertainty, but only at the cost of a serious lack of detailed information on the structure, because angular resolution is relatively poor, even with the largest existing telescopes. The largest, the 300-foot (91-m) transit telescope of the National Radio Astronomy Observatory at Green Bank, West Virginia, has a beamwidth of 10′ (arc) at 21 cm, which is larger than the angular dimensions of all but the closest external galaxies.

The closest external systems are, of course, *the Magellanic Clouds*, which have been extensively studied by the Sydney group. These systems are more than an order of magnitude less massive than our Galaxy, and hence are not directly comparable to the

*This work was supported in part by the Joint Services Program (Contract DA 36-039-AMC-03200 (E)).

Milky Way System. On the other hand, the proximity of the Magellanic Clouds allows us to study in detail the interrelationships of the dust, gas, and stars. The evidence so far indicates that the two systems are rather different, the Small Cloud being an assemblage of gas complexes, possibly not stable, while the Large Cloud is, from the latest observations of McGee and Milton, a spiral galaxy. The relationship of the gas to the observed stars is not entirely clear yet.

The next closest major system is the *Great Nebula in Andromeda* (M 31), which is a very massive one, comparable to or even larger than the Milky Way System. The major studies of this system have so far been those utilizing the 300-foot telescope at 21 cm wavelength. Burke and Turner made observations along the major axis and at selected intervals perpendicular to the major axis. Roberts has studied the central portions, taking drift scans across the Nebula. Both studies have shown that the hydrogen is much less dense in the central regions, reaching a maximum about 1° from the center, where the abundance of bright OB-associations is also greatest.

The *rotation law* was derived in different ways by the two groups, but the general conclusion is that complete circular symmetry in the rotation is an unwarranted assumption, although there is no full agreement upon the magnitude of the deviations. There are certainly deviations of 10 to 20 km/sec at all distances from the center, while in the region between 20 and 40 minutes of arc from the center the deviations may be as great as 40 km/sec.

The difficulty in deriving a unique rotation law led Burke and Turner to describe the north-following (NF) and south-preceding (SP) halves separately. The SP half is particularly interesting because of the existence of a discrete, detached region approximately 110 minutes of arc from the center, which they call the *south-west companion*. Since the south-west companion is close to the major axis, and travelling at approximately the correct (rotational) velocity, it is tempting to pass the rotation curve through it. Such a procedure is evidently dangerous, because there is no need for such a discrete cloud to be in a circular orbit. In fact, its mass is approximately 10^8 solar masses, which makes it comparable to the Small Magellanic Cloud. Consequently, the south-west companion might well be the raw material for a companion galaxy in which star formation conditions are not yet favorable. A few Cepheids and OB stars are visible in the companion, but the ratio of stellar mass to hydrogen mass is at least two orders of magnitude less than in the prominent spiral arms.

A mean rotation law resembles neither the Brandt nor the Bottlinger-Lohmann empirical laws, and it appears somewhat dangerous to derive a *mass* from a fit to either. A direct determination, using the NF hydrogen data only, gives a mass of $2{\cdot}4 \times 10^{11}$ solar masses, somewhat lower than previous estimates. Perhaps the most valuable use of the hydrogen rotation laws is to indicate the uncertainties in present mass estimates from dynamical data only.

Roberts agrees with Burke and Turner that the concentration of neutral hydrogen is greatest where the concentration of OB stars is greatest. Detailed comparison shows clear *relationships between the 'star' arms and 'gas' arms* along the NF half, while the agreement is less good along the SP half, where the stellar spiral structure is less clearly defined, and no resolution of gas arms is observed.

The *comparison of M 31 with the Milky Way System* is interesting, since the masses of both systems are nearly the same, particularly so when we use the larger (10-kpc) scale

factor for our Galaxy and the new hydrogen mass for M31. In fact, if one assumes that the distance of M31 is 600 kpc and that the distance from the Sun to the galactic center is $R_0 = 11$ kpc, the rotation laws for the two systems are identical within the observational scatter. In one respect, however, the two systems are dissimilar: the spacing between spiral features is nearly twice as great in M31 as in our own Galaxy. This would imply that our Galaxy is more tightly wound, i.e. of earlier type. The star-formation rate, on the other hand, is greater in our own Galaxy than in M31, and this would imply that our Galaxy is of later morphological type. This apparent discrepancy in relative type is not yet resolved, and may indicate that there are tightly-wound spirals that exhibit the high star-formation rates typical of the Sc galaxies, unless our identification of morphological type is completely wrong for the Milky Way System.

M 33 and NGC 6228 have both been studied with the 300-foot telescope, but the results have not been discussed in detail. M33 exhibits a rotation law similar to that of M31, with a central depletion of hydrogen, and a strong shear to the region of maximum star formation, where the velocity of rotation is nearly constant. A number of *fainter galaxies* have been studied by Roberts, who finds evidence for 'hydrogen companions' similar to the south-west companion of M31. No definite conclusions on rotation laws appear warranted for these more distant systems, because non-symmetric hydrogen distributions can not be resolved. With the Owens Valley interferometer, the Cal Tech group has done interesting work, which demonstrates the complex hydrogen structure of spiral galaxies.

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32. THE HYDROGEN DISTRIBUTION IN GALAXIES

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ABSTRACT

Results of 21-cm line observations with the 300-foot telescope are summarized. Along the major axis of M 31, the peaks in the distribution of neutral hydrogen correlate closely (but do not exactly coincide) with the optical spiral arms. The distribution of hydrogen over the galaxy shows a ring pattern; the same is true in M 33.

Resolution of such ring structures may be facilitated by consideration of profile integrals over a restricted velocity range around the systemic velocity. Out of nine spiral systems studied, with minor axis $\geqslant$ 10′ (arc), only NGC 628 exhibits no ring. The ratios ring radius to ring width and optical radius to ring radius vary little about averages 2·5 and 1·7. In two irregular galaxies, no ring structure was observed.

Neutral-hydrogen haloes, if present, can only be studied in large edge-on systems. In NGC 4244 and 7640, the upper limit to the density of neutral hydrogen in the halo is 0·001 cm^{-3}. Qualitative considerations indicate that a similar value may apply in the Galaxy.

1. INTRODUCTION

Meaningful detail on the distribution of neutral atomic hydrogen in galaxies is derivable only for those systems where the ratio of galaxy size D to antenna-beam size β is large. In the northern hemisphere, for example, the most favorable case of large D/β is that of M31 observed with the 10′ beam of the NRAO 300-foot (91-m) telescope; in this case $D/\beta \approx$ 20. The optical major-axis diameter (Holmberg 1958) used in this ratio gives a lower limit to D since, as discussed below, the hydrogen extent is larger than the optical size, which refers to a sky-limited isophote of $26^m\!.5$ per square second of arc. The parameter derived observationally is $T_b^*(x, y, V)$, the 21-cm brightness temperature as convolved by the antenna beam pattern, centered at a point on the image of a galaxy whose coordinates are x, y, and at a radial velocity V within an interval $\pm\Delta V$. For small opacity, $T_b^*(x, y, V)$ is directly proportional to $N^*(x, y, V)$, the projected surface density.

2. THE ANDROMEDA NEBULA, M31

Figure 1 presents a contour map of the quantity $\int T_b^*(x, y, V)\,dV$ for M31, given in units of brightness temperature (°K) × km/sec. The peak-contour ridge is drawn as a heavy solid line in the central region and as a dashed line in the outer sections. The map also shows the locations where the optical arms cross the major axis as defined by Baade (1958), as well as radio continuum sources near or within the region bounded by the contours.

The most striking feature in the contour map is the *ring-like distribution* of the central peak-contour line. The presence of this gross feature in the distribution of neutral

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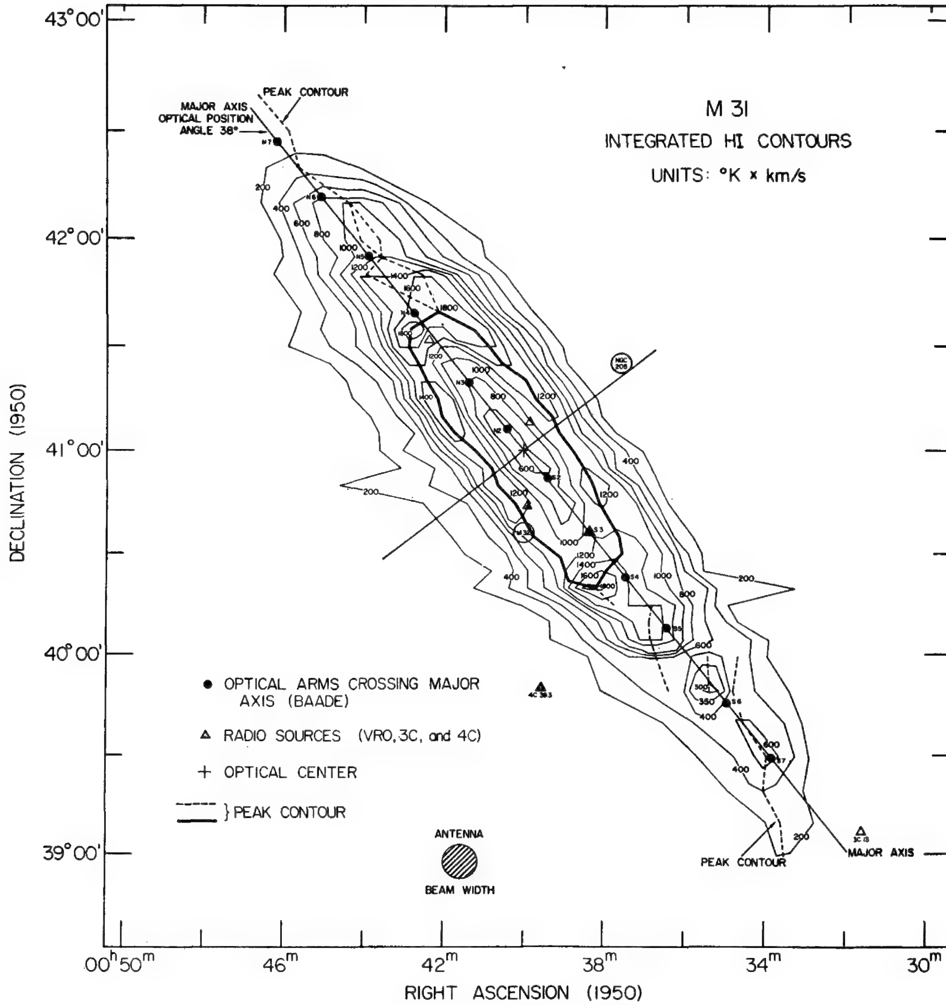

FIG. 1. The observed distribution of 21-cm line radiation from M 31. The quantity plotted is the integral of the observed line profile at each position. The ring structure of neutral hydrogen is shown by the heavy contour, which represents the ridge line of peak-contour levels. The dashed line follows the peak-contour ridge in the outer regions of M 31.

hydrogen in M31 has been noted previously by Burke *et al.* (1964), by Roberts (1966), by Brundage and Kraus (1966), and by Gottesman *et al.* (1966). The radius of this ring is 10·3 kpc for an adopted distance to M31 of 690 kpc. The profiles of the integrated distribution of neutral hydrogen along the major and minor axes are shown in Figure 2. Assuming a Gaussian shape for the ring, we find an average dispersion, $\sigma = 5{\cdot}3$ kpc (corrected for beam-smearing). Thus the ring structure is quite broad.

Figure 2 also displays, as bars, the locations of the crossings of optical arms with the

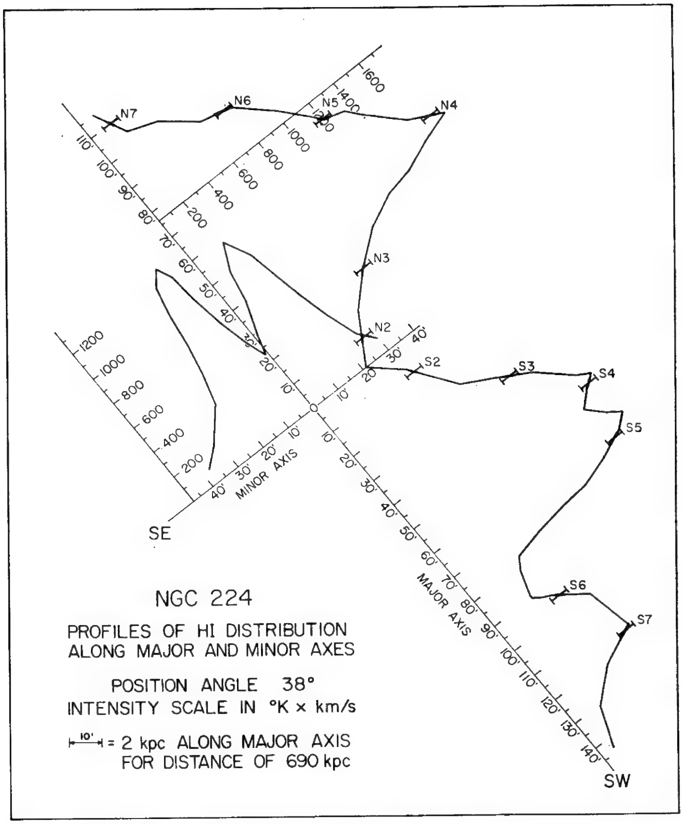

FIG. 2. Profiles along the major and minor axes of the distribution of 21-cm line radiation from M 31 (cf. Figure 1). The bars along the major-axis profile are the locations of optical arms crossing the major axis as defined by Baade.

major axis. The width of these bars is drawn to scale, so as to correspond to 500 pc. Several of the optical-arm crossings lie close to peaks in the neutral-hydrogen distribution, but *there is no exact coincidence*. Thus, the center of N 4 is about 600 pc north of a hydrogen peak, and the centers of S 4 and S 5 are about 400 and 1100 pc, respectively, south of hydrogen peaks. N 6 and S 7 are also close to secondary peak features in the distribution of neutral hydrogen.

3. HYDROGEN RING STRUCTURE IN OTHER SPIRALS

The second largest spiral visible from the northern hemisphere is M 33. A map of its integrated-hydrogen contours, derived from 300-foot observations (Gordon 1966), also displays a ring-shaped distribution; its radius is 20′ and its dispersion $\sigma = 8'.5$. For a distance of 720 kpc, these correspond to $R_r = 4{\cdot}2$ kpc and $\sigma_r = 1{\cdot}9$ kpc. Meng and Kraus (1966) have reported a similar ring distribution for the neutral hydrogen in M 33.

Although the peak hydrogen contours for M 33 are well separated, their outline is not

as striking as in M31, and one can easily anticipate that, with the 300-foot telescope, beam-smearing would hide any ring structure in galaxies whose minor-axis angular extent is about one-half or less that of M33. However, contours of neutral hydrogen summed over a limited radial-velocity range will, under favorable circumstances, yield information on possible ring structure in smaller galaxies. Consider the locus of the systemic radial velocity, S, mapped on the image of a galaxy. This locus, for a system in pure rotation (with any rotation law), will be a straight line along the minor axis of the galaxy. A map of the observed hydrogen distribution for a radial-velocity range $S \pm \Delta V$ will then represent the combined distribution of (*i*) the loci for $S \pm \Delta V$, (*ii*) the distribution of neutral hydrogen, (*iii*) the random motion of the hydrogen, and (*iv*) the smearing effect of the antenna. Such a map, for a true ring distribution of the hydrogen, will have two peaks on the minor axis, with a minimum at the center of the galaxy. To find such

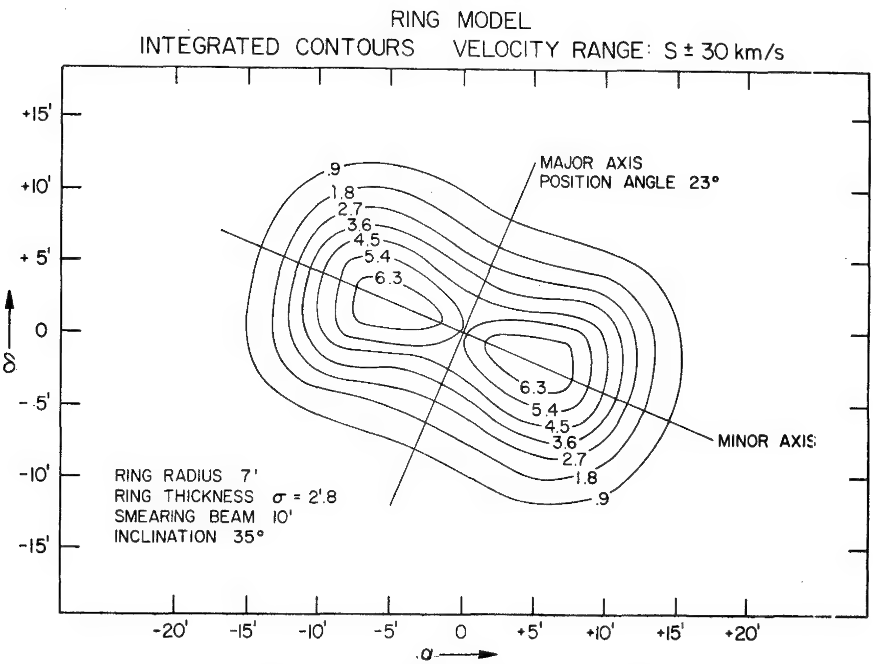

FIG. 3. A computer-generated contour diagram for a model galaxy. Only a limited velocity range centered on the systemic velocity, S, was used. The contour-level scale is arbitrary.

detail we require that the ring diameter along the minor axis be at least comparable to the half-power beam size and that the random motion of the hydrogen be small. Figure 3 shows such a map for a model galaxy having a true ring distribution of neutral hydrogen. Note that the major axis of the galaxy lies along the narrow part of the hydrogen distribution, since the velocity interval for the contours is centered on S, i.e., along the minor axis. For comparison, Figure 4 presents observed contours for M33 for a similarly restricted velocity range.

Minor-axis regions are best suited for such tests of ring structure, because the systemic

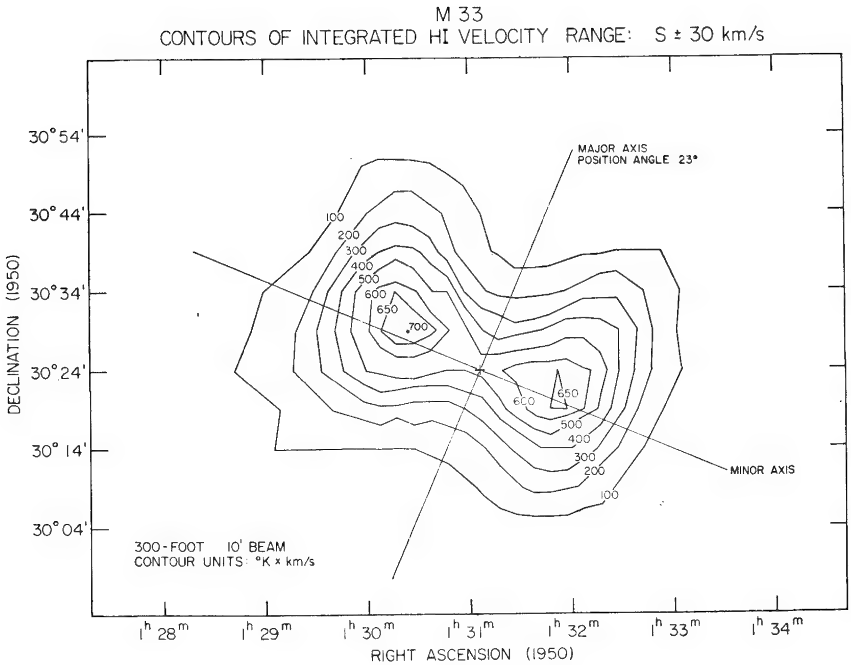

FIG. 4. Contours of brightness temperature, integrated over a limited velocity range centered on the systemic velocity, S, for M 33. The contour scale is proportional to brightness temperature. Compare with Figure 3.

radial-velocity locus is a straight line, and for this velocity condition the ring has its greatest separation. For other radial velocities the loci will be curved and the 'resolution in phase space' will become poorer. For examples of model radial-velocity loci see Roberts (1966, 1967). The interpretation of contours such as those in Figures 3 and 4 is unique, namely a ring, unless very arbitrary distribution functions are invoked. As galaxies of smaller angular size are considered, the two peaks in Figure 3 will merge and the interpretation of the resultant profile along the minor axis is no longer unique; a disk distribution of hydrogen could also explain such a flat-topped profile. However, it would seem unreasonable if the derived true distribution of hydrogen were to vary with the angular size of the galaxy. In the summary below we will attribute a ring structure to systems whose profiles of hydrogen distribution along the minor axis for $S \pm \Delta V$ are flat-topped. As still smaller systems are considered, the two peaks merge completely and no unambiguous conclusions can be drawn.

The extent of random and non-circular motions may also limit the success of this approach. Further, if the hydrogen has a significant component of z-motion, i.e., perpendicular to the plane of the galaxy, the inclination of the system will be an additional parameter in the analysis. NGC628, a close to face-on galaxy, is an example where large random motions (several tens of km/sec) and/or large z-motions are present. This conclusions follows from the extent of contours drawn for velocity intervals of 20 km/sec

(a single channel width for the twenty-channel receiver used in these observations). The half-width of these contours—measured in any position angle—is significantly larger than the beam size, indicating a distribution in that velocity range over much of the optical extent of the galaxy. Of the galaxies with minor-axis sizes exceeding 10′, NGC628 is the only one studied thus far that does not show a ring distribution of hydrogen. This may be due either to the actual absence of a ring or, more likely, to the failure of the technique of analysis for a 10′ beam, because of the large random motions.

The Holmberg (1958) catalogue lists thirteen spirals with minor axis > 10′. An additional large system not in his catalogue is IC342, with estimated dimensions of 40′ × 33′ (Shapley and Seyfert 1935); it is the third largest in the northern hemisphere. Sufficient 300-foot data are available for nine of these systems to allow analysis of their neutral-hydrogen distribution. Eight of these nine systems show a ring distribution of their hydrogen; the remaining system is NGC628 discussed above. Table 1 lists various parameters for these nine galaxies. The structural type and size are from Holmberg (1958), except for IC342; the distances are from De Vaucouleurs (1967). Angular values for the ring radius, R_r, and width, σ_r, are given in columns 5 and 6; corresponding linear sizes are given in columns 8 and 9. The linear size, R_{opt}, based on the optical radius along the major axis is in column 7. No values of R_r and σ_r are given for NGC3031 (M81) since the systemic velocity, -44 km/sec, is confused with galactic hydrogen and the analysis described above cannot be made. That a ring *is* present, is clearly evident in the double-peaked drift curves obtained at various velocities and declinations. NGC5055 and 6946 are examples of systems whose profiles along the minor axis, in the contour diagram for a velocity range of $S \pm 30$ km/sec, are flat-topped; the ring radii are therefore uncertain, and no values for the ring width could be derived.

Parameters for the 'ring' of hydrogen in our own Galaxy are included in Table 1 (Kerr and Westerhout 1965, Figure 17). This example points up several factors important in describing the hydrogen distribution by a ring. First, there may be structure in the ring. There is sufficient relative resolution to show this in M31 (see Figure 2). Second, the thickness may not be uniform around the ring, and the fitting of a Gaussian curve is merely a convenience to obtain a parameter descriptive of the ring thickness. The values of σ_r quoted are generally averages of measurements which may show a range of up to fifty per cent. Similarly, the values R_r are averages. About two-thirds of the neutral hydrogen in a galaxy can be associated with the ring structure. The remainder may be attributed to a disk distribution which extends beyond the optical dimensions of the galaxy. Thus, in M31 the observed (i.e., uncorrected) extent of the neutral hydrogen, extrapolated to a zero contour level, is 270′ compared to an optical major diameter of 197′. The correction for 10′ beam-smearing in this case is quite small.

It is important to note that the use of a ring and a disk to describe the hydrogen distribution represents a simplified model, but one that is much more realistic than Gaussian or uniform distributions. The important observational result is, that there is a ***minimum*** in the hydrogen distribution in the central regions of a spiral, and a ***maximum*** at about one-half the optically measured radius.

The average value of R_r/σ_r for the galaxies in Table 1 is 2·5, for R_{opt}/R_r it is 1·7. The scatter of individual ratios about these averages is comparatively small, while the individual linear dimensions of galaxy size, ring radius, and thickness, each have a range of more than a factor of two. The galaxy types represented in this sample cover early Sb to late Sc.

Table 1

Parameters of galaxies studied for ring structure in neutral hydrogen

(1) NGC number	(2) Type	(3) Opt. Size (min arc)	(4) Distance (Mpc)	(5) R_r (min arc)	(6) σ_r (min arc)	(7) R_{opt} (kpc)	(8) R_r (kpc)	(9) σ_r (kpc)	(10) R_r/σ_r	(11) R_{opt}/R_r
224 (M 31)	Sb⁻	197 × 92	0.69	51	26	19·8	10·3	5·2	2·0	1·9
598 (M 33)	Sc⁺	83 × 53	0.72	20	8·9	8·7	4·2	1·9	2·2	2·1
628 (M 74)	Sc⁻	12·0 × 12·0	7·8	*	*	13·6	—	—	—	—
2403	Sc⁺	29 × 15	2·5	8·9	3·3	10·6	6·5	2·4	2·7	1·6
3031 (M 81)	Sb⁻	35 × 14·4	2·5	*	*	12·7	—	—	—	—
5055	Sb⁺	16 × 10·1	4·6	4·0:	*	10·7	5·4:	—	—	2·0:
5457 (M 101)	Sc⁻	28 × 28	4·6	8·5	3·8	18·8	11·4	5·1	2·2	1·6
6946	Sc⁻	14·4 × 12·6	3·7	5·7:	*	7·8:	6·2:	—	—	1·3:
IC 342	Sc⁻	(40 × 33)	2·1	17	5·3	12·2	10·4	3·2	3·2	1·2:
Milky Way	Sb-c	—	—	—	—	—	7·7	3·0	2·6	—

Explanation of symbols: R_r = ring radius, σ_r = ring width (dispersion), R_{opt} = optical radius.

*See text.

Two irregular-type galaxies of large angular size, NGC 6822 and IC 1613, do not show any prominent ring structure. We may conclude either that they do not have rings on the dimensional scale of the spirals, or that the large random motions (as deduced from an analysis similar to that described above for NGC 628) prevent any rings from being observed with a 10′ beam.

4. NEUTRAL HYDROGEN IN THE HALO REGIONS OF SPIRAL GALAXIES

A search for a low-density neutral-hydrogen halo in our own Galaxy is not possible, because of the confusing effect of local hydrogen. A search for halo hydrogen in other galaxies of inclination $< 85°$ would be similarly confused by hydrogen in the plane of that galaxy. To derive information on such haloes, we require systems seen essentially edge-on, of relatively large angular size, and free of companion galaxies which could cause tidal effects. Two such systems are NGC 4244 and 7640. Their optical angular dimensions (Holmberg 1958) are $18' \times 2'.9$ and $13'.5 \times 3'.6$, and their distances are 3·8 and 4·4 Mpc, respectively. These two systems have been completely mapped with the 300-foot telescope, with observations spaced every 5′, out to 15′ from the optical center. The resultant contours show no measurable broadening along the minor axis of either system. This is consistent with a thickness of about 500 pc or less for the layer of hydrogen, which would correspond to at most $0'.5$ at the distances of these galaxies.

The contour diagrams also yield upper limits to the brightness temperature for the halo regions of these galaxies. From this upper limit and the path length through the halo, we find that for z-distances exceeding 5 kpc, the number density of neutral hydrogen is smaller than $1 \times 10^{-3}\ \mathrm{cm}^{-3}$. Two assumptions are made here: (1) the radial-velocity range in the halo is similar to that of the galaxy, since the integration over velocity was made for a range only little larger than the observed range found in the plane; (2) the spin temperature is higher than the background temperature.

Can this result be extended to our Galaxy? The following factors will determine the relative density of haloes in various stellar systems; each factor must be evaluated before we may answer this question: (1) the total neutral-hydrogen content, (2) the gravitational attraction in the z-direction, (3) possible interstellar mixing mechanisms and pressure effects, and (4) sources of neutral hydrogen. We shall assume that the conditions determining the state of ionization are similar for late-type spirals and for intermediate systems such as our Galaxy.

The neutral-hydrogen content for one of these systems, NGC 4244, has been measured previously (Roberts 1962) and is comparable to that in the Galaxy, as is the case for Sc-type systems in general (Roberts 1967). Any scaling factor for haloes based on a comparison of the total hydrogen content for Sc-type systems to that in the Galaxy is less than two. We may estimate the z-component of the gravitational attraction by approximating the mass distribution in a spiral galaxy by a thin uniform disk. For such a geometry and at similar z-distance, we find for the Galaxy an attractive force larger by a factor of about two than for Sc-type systems. This would tend to reduce the halo hydrogen in our Galaxy compared to the measured systems.

Unfortunately items (3) and (4) above are difficult to evaluate. We have little quantitative knowledge on pressure or mixing mechanisms or on sources of neutral hydrogen, e.g. accretion from the inter galactic medium, or the possibility that hydrogen in the halo results from mass loss by evolving stars (Pikel'ner and Šklovskij 1959). An estimate for

this latter contribution may be made by a comparison of average surface densities of galaxies. We assume here that they are of similar ages. Such an approach would imply a small excess, less than a factor of 2, of neutral hydrogen at high z in our Galaxy.

We conclude that, except for unknown pressure effects and the possibility of accretion, it appears reasonable to apply an upper limit of 1×10^{-3} cm^{-3} on the density of neutral atomic hydrogen in the halo of our Galaxy.

REFERENCES

Baade, W. 1958, in *Stellar Populations*, Ed. D. J. K. O'Connell, S. J., North-Holland Publ. Cy., Amsterdam, p. 3 (also in 1958, *Ric. astr. Specola astr. Vatic.*, **5**, p. 3).

Brundage, W. D., Kraus, J. D. 1966, *Science*, **153**, 411.

Burke, B. F., Turner, K. C., Tuve, M. A. 1964, in Annual Report of the Director, Dept. of Terrestrial Magnetism, 1963–64, *Carnegie Instn. Washington Year Book*, **63**, p. 341.

De Vaucouleurs, G. 1967, in *Galaxies and the Universe*, Eds. A. and M. Sandage, Vol. IX in the series: *Stars and Stellar Systems*, Univ. of Chicago Press, Chicago, Chapter 17 (in press).

Gordon, K. 1966, private communication.

Gottesman, S. T., Davies, R. D., Reddish, V. C. 1966, *Mon. Not. R. astr. Soc.*, **133**, 359.

Holmberg, E. 1958, *Medd. Lunds astr. Obs.*, Ser. 2, no. 136.

Kerr, F. J., Westerhout, G. 1965, in *Galactic Structure*, Eds. A. Blaauw and M. Schmidt, Vol. V in the series: *Stars and Stellar Systems*, Univ. of Chicago Press, Chicago, p. 167.

Meng, S. Y., Kraus, J. D. 1966, *Astr. J.*, **71**, 170.

Pikel'ner, S. B., Šklovskij, I. S. 1959, *Ann. Astrophys.*, **22**, 913.

Roberts, M. S. 1962, *Astr. J.*, **67**, 437.

Roberts, M. S. 1966, *Astrophys. J.*, **144**, 639.

Roberts, M. S. 1967, in *Galaxies and the Universe*, Eds. A. and M. Sandage, Vol. IX in the series: *Stars and Stellar Systems*, Univ. of Chicago Press, Chicago, Chapter 11 (in press).

Shapley, H., Seyfert, C. K. 1935, *Harvard Bull.*, no. 899, 16.

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33. NARROW-BAND OBSERVATIONS OF NEUTRAL HYDROGEN IN GALAXIES

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ABSTRACT

From a survey with 50 kHz bandwidth, a correlation between H I and H II regions in M 31 is suggested; the SW companion appears connected to the main body of the system. In M 33 the distribution of hydrogen is asymmetric with respect to the major axis.

We have recently completed new observations of the largest nearby galaxies, with a bandwidth of 50 kHz $\approx$ 10 km/sec. The earlier survey of the southern regions of M31, in which Gottesman *et al.* (1966) used a 200-kHz band, had shown many interesting features requiring further study with a narrower band and higher sensitivity. The rotation curve appeared to be significantly different in the NE and SW sections. Other points of interest were the irregularity of the density distribution of neutral hydrogen, and the apparent correlation between the neutral-hydrogen concentrations and the H II regions along the major axis.

Taking series of drift curves at 7′ (arc) separation in declination, we have completely surveyed both M31 and M33. Although the reduction of the data is not yet finished, several contour maps at constant velocity relative to the local standard of rest are ready for both galaxies.

The observations of M31 are being reduced by S. T. Gottesman. The survey extends 170′ (arc) along each half of the major axis, and the frequency range covered is 1·5 MHz ($\approx$320 km/sec) on either side of the central frequency of the galaxy. Figure 1 shows the results of the preliminary reduction of observations at a frequency of +2·5 MHz relative to the local standard of rest. The neutral hydrogen has a maximum concentration at a distance (x) along the major axis of $-60'$, in agreement with expectation. There is, however, a deficiency of hydrogen at $x = -80'$ and a secondary maximum at $x = -110'$. The latter was described by Burke, Turner and Tuve (1964) as the south-west companion of M31. The present data are consistent with the view that this hydrogen may be a part of the main structure of M31: the contours indicate a continuous connection between the main concentration at $x = -60'$ and the hydrogen at $x = -110'$; also, the observations at nearby frequencies show no break in frequency between the two concentrations which would justify taking the hydrogen at $x = -110'$ as a separate object distinct from the main body of the galaxy.

It is of particular interest to compare this map with the distribution of H II regions studied by Baade and Arp (1964). The H I concentration at $x = -65'$, $y = +10'$ coincides closely with the strongest grouping of H II regions in the SW part of M31. The neutral hydrogen at $x = -110'$ is at the position of Baade's spiral arm S7, in which only one H II region is catalogued by Baade and Arp. This is evidently an arm in which

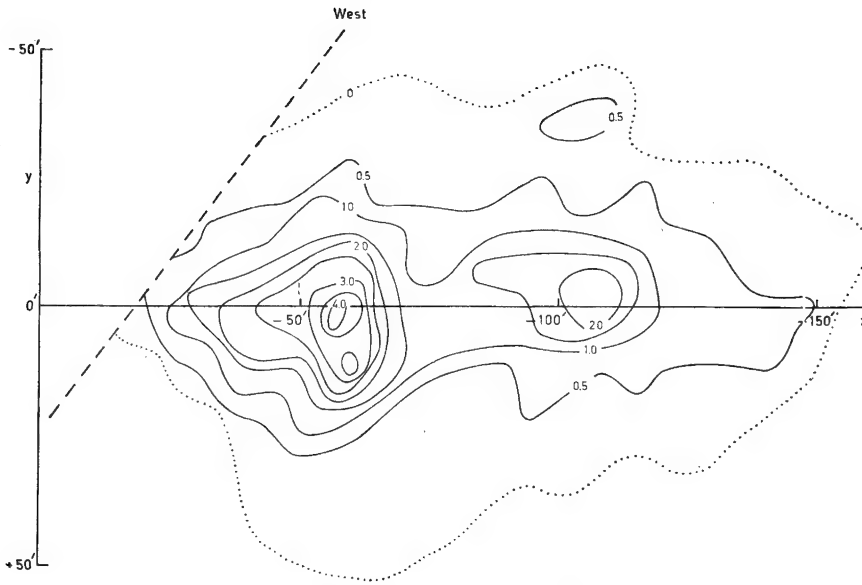

FIG. 1. Contour map of neutral hydrogen in the south-preceding half of M 31 at a frequency of + 2·5 MHz relative to the local standard of rest. The bandwidth is 50 kHz. The contour values are given in °K of aerial temperature. The dotted line gives the probable outer limit of neutral hydrogen observed at this frequency. The dashed line runs east-west and indicates the direction of the drift scans. The origin of the x, y system is at the centre of M 31.

star formation has not progressed as far as it has in the arm near $x = -60'$ (Baade's arm S 5). Contour maps such as that in Figure 1 will allow a more direct comparison between the distributions of H I and H II regions. We note that the coincidence observed at $x = -65'$, $y = +10'$ does not necessarily mean that the ionized and neutral regions coincide in space; however, they probably lie within the same complex of higher gas density than average.

The reduction of the data for M 33 is being undertaken by G. de Jager. The observations cover a range of 210 km/sec (1 MHz) on either side of the central velocity of the galaxy. In most regions the observations were spaced at frequency intervals of half a bandwidth, because of the narrow spectra found in many areas of the galaxy. Figure 2 shows maps at two frequencies almost symmetrical relative to the central velocity. The position angle of the major axis was taken as 23°. Two features of these maps warrant some comment. Firstly, the amount of hydrogen in the NF map is 1·6 times greater than that in the SP map. Secondly, both maps show strong asymmetry, with enhanced surface density towards decreasing position angle. There are very few optical data at these distances from the centre of M 33; therefore no direct correlation with optical features is possible. However, when the reductions are complete, it will be interesting to see whether these regions of enhanced neutral-hydrogen density are extensions of the outer spiral arms of M 33. Further studies of optical features (e.g. H II regions or other spiral-arm tracers) are required so that correlations with the neutral-hydrogen features can be sought.

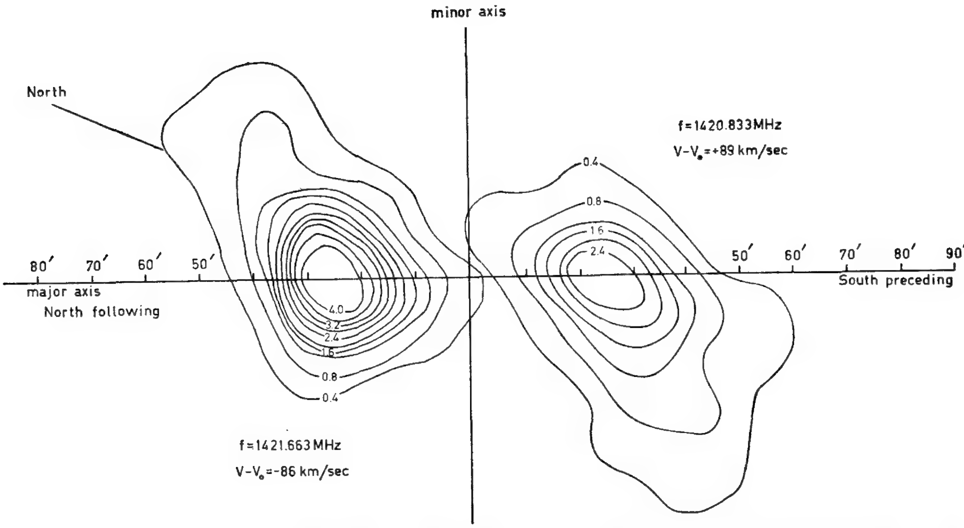

FIG. 2. Contour maps of neutral hydrogen in M 33 observed at two frequencies. The corresponding velocities are almost symmetric with respect to the velocity, V_0, of the centre of the system.

REFERENCES

Baade, W., Arp, H. C. 1964, *Astrophys. J.*, **139**, 1027.
Burke, B. F., Turner, K. C., Tuve, M. A. 1964, *Carnegie Instn. Washington Year Book*, **63**, 341.
Gottesman, S. T., Davies, R. D., Reddish, V. C. 1966, *Mon. Not. R. astr. Soc.*, **133**, 359.

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34. EXTRAGALACTIC 21-CM WORK AT NANÇAY

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The radiotelescope at Nançay has made its first test observations of extragalactic 21-cm radiation. The receiver is a correlation receiver using a hybrid junction. The main program aims at getting information on the overall properties of numerous faint galaxies. The number of channels is only 15; their width is 280 kHz = 59 km/sec, so that the line profile for a typical galaxy occupies about half the total passband of 4·2 MHz ≈ 900 km/sec.

Figure 1 shows the result of four half-an-hour observations on NGC3109; we find the zero line for each of them by subtracting an observation made on a blank comparison field. NGC3109 gives the profile of 2 °K peak intensity on the right; the complex profile in the zero-velocity region is due to 21-cm line radiation from our Galaxy entering through various side lobes.

More detailed accounts of this work have been published elsewhere (Blum *et al.* 1966, Bottinelli *et al.* 1966).

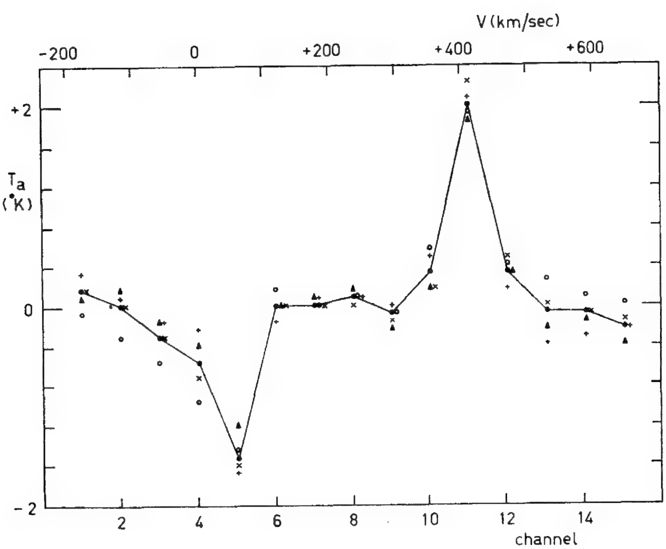

FIG. 1. 21-cm profile of NGC 3109, observed at Nançay with 59 km/sec bandwidth. Velocities are with respect to the Earth. The 2 °K peak at $V \approx +400$ km/sec is due to NGC 3109; the negative profile around zero velocity comes from galactic radiation.

The profile was measured four times, on 21 March (open circles), 22 March (triangles), 25 March (crosses) and 8 April 1966 (plus signs); the average result is shown by filled circles joined by a broken line.

REFERENCES

Blum, E. J., Delannoy, J., Le Roux, E., Weliachew, L. 1966, *C. r. hebd. Séanc. Acad. Sci.*, Paris, **262**, sér. B, 1640.

Bottinelli, L., Gouguenheim, L., Heidmann, J., Heidmann, N., Weliachew, L. 1966, *C. r. hebd. Séanc. Acad. Sci.*, Paris, **263**, sér. B, 223.

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35. DISCUSSION ON NEUTRAL HYDROGEN IN GALAXIES

Mrs N. H. Dieter asks Roberts: Does M101 show asymmetry in the distribution of neutral hydrogen like that apparent in M33?

M. S. Roberts answers: M101 has been completely mapped with the 300-foot Green Bank telescope. The position angle derived from the contours of integrated hydrogen agrees with the values found by Miss Volders (1959) and by Mrs Dieter (1962) from earlier 21-cm studies. M101 has a ring of neutral hydrogen whose parameters are similar to those found in M31, M33, and IC342. In addition, there is a suggestion that M101 has a neutral-hydrogen companion.

B. J. Robinson: In observations of southern galaxies at Parkes we find that in the majority the rotation curve is asymmetrical.

One interesting case is that of NGC300: there is an adjacent neutral-hydrogen cloud which appears to be a 'companion'. In the inner parts of NGC300 the 21-cm isophotes have the same major axis (position angle 109°) as the stellar distribution. However, the axis of the outer 21-cm isophotes is twisted to about 148°, pointing in the direction of the companion.

A similar distortion is seen in the velocity contours. In the inner part the contours are aligned perpendicular to the optical axis, as expected. But the contours for the extreme velocities form closed loops well off this axis, lying instead close to the line with position angle 148°. The 'companion' therefore appears to have a pronounced influence on the velocity field in this galaxy.

G. W. Rougoor: The interferometric investigation by Seielstad and Whiteoak (1965) of 21-cm radiation from external galaxies has been continued and thirty galaxies have now been analyzed. We have found that it is not possible to derive a rotation curve with a single spacing of the interferometer; the conclusion from the earlier investigation that solid-body rotation extends over large distances in a majority of galaxies, appears invalid now. Computation has shown that, if one puts systems like our Galaxy and M31, for which both rotation curve and density distribution are well-known, at distances such that they have diameters of 10′ to 15′, representative of the galaxies in our investigation, the curve giving phase (or, position) as a function of velocity always becomes a straight line. By making model computations such as done by Epstein (1964) one can derive masses for the galaxies but no good rotation curves. The only way out is to do a complete synthesis. This should make it possible to determine a good rotation curve for a regular spiral system like M81. (See note on page 207.—*Editor*.)

J. E. Baldwin: (*a*) In his discussion of M31, Roberts noted that, projected on the equatorial plane, one minute of arc corresponds to 1 kpc. In fact 1′ corresponds to 200 pc along the major axis, and the coincidence or not of neutral hydrogen and optical spiral arms should not be difficult to decide. (*b*) Is there a disagreement between Roberts' results (Paper 32), showing a poor correlation of H I and H II arms in M31, and those of Davies (Paper 33), which suggest there is quite good correlation?

Roberts answers: (*a*) Baade's data on the optical arms in M31 (Paper 32, Figure 1) refer to positions where they cross the major axis. However, there are essentially no regions of peak hydrogen density along this axis. Comparison between the peak contours of neutral hydrogen and the distribution of H II regions mapped by Baade and Arp (1964) must therefore be made in areas off the major axis, and the projection factor caused by the tilt of the galaxy must be considered; along the minor axis 1′ is close to 1 kpc.

(*b*) One of the slides shown by Davies displayed the neutral-hydrogen distribution as well as the distribution of H II regions. There was a gross agreement only, not one of detail. My 300-foot observations (Roberts 1966) show a similar result.

S. B. Pikel'ner: I should like to propose an interpretation of the ring-like structures observed and call for checks on an observable sequence deduced from this. The thickness of spiral arms should grow with distance R from the centre of a galaxy, owing to the decrease of the stellar density and, consequently, of the gravitational potential. As the gas density in the arms is roughly constant over a wide range of R, the surface density of the gas should increase outwards. In the outermost parts of a galaxy, volume density and surface density of the gas both decrease. Thus, the expected distribution of surface density looks like a ring.

The width and the radius of the ring should depend on the type of the galaxy. Sa galaxies have a big, dense halo and thin arms. Only at large distances from the centre the thickness of the arms increases, but the density of the gas is not high there. So Sa galaxies should have rings with big radii. The halo of Sc galaxies is not dense; the thickness of the arms is determined mainly by the density of the gas, and the surface density should therefore be about constant in a wide ring, the inner radius of which should be relatively small. In Irr galaxies the surface density should be rather uniform.

I should like to ask if such a dependence of ring shape on galaxy type is observed in spiral galaxies.

Roberts answers: A systematic variation of hydrogen ring parameters with the structural type of galaxies would be a most valuable datum in understanding galactic structure. According to the present data for six galaxies (Paper 32, Table 1), the dimensionless ratio R_r/σ_r, ring radius to ring thickness, is approximately constant; the ratio of total radius to ring radius also appears to be approximately constant. M31, an Sb$^-$, and M33, an Sc$^+$, two well-investigated nearby systems, have the same values for these ratios. However, in keeping with your remarks, I should point out that NGC6822, an irregular-type system, does not show a ring of hydrogen, although it is of large enough angular size for one to have been found if it had the properties of the rings in spirals. The hydrogen radiation from Sa-type galaxies is too weak for any such analysis.

B. F. Burke: I want to clarify the concept of a 'ring' of neutral hydrogen. In M31 the hydrogen begins to be detected with certainty at about 20′ or 30′ from the centre; it rises to a maximum density at about 60′, then falls to a low density around 90′ and remains observable, in parts at least, to a distance of 130′ to 150′. On the SP side the peak is at 60′, but on the NF side the 21-cm maxima lie 10′ to either side. Whether one calls such a distribution a 'ring' or not – it looks more like a disk with a hole in the middle –, I would caution theoreticians against explaining mathematically perfect rings rather than spiral gas distributions. Within a broad 'ring' the gas still may be concentrated along spiral loci.

B. J. Bok comments: On the other hand: Arp (1964; see also Baade and Arp 1964) finds a very narrow ring of H II regions, nothing like a thin disk with a hole in the middle.

Burke answers: The majority of Arp's emission regions are seen along ridges parallel to the major axis; they are subject to marked projection effects, because of the high inclination of M31.

Roberts: I am in complete agreement with Burke's remark. In our model-fitting program we approximate galaxies by a ring superposed on a disk of hydrogen; about two-thirds of the neutral hydrogen is in the 'ring'.

J. H. Oort: In connection with the 'hole' in the neutral-hydrogen disk of the Andromeda Nebula, I wish to point out that absorption is present over the entire disk and appears to increase towards the centre. It is tempting to conclude from this that there must also be a large density of hydrogen in the central region, but that most of it is in molecular form. The same might then very well hold for our own Galaxy.

As regards Sa nebulae there is certainly evidence of real rings. The best-studied example is NGC4594, where there is an absorbing ring extending between about 100″ and 400″ from the centre; in this case there is convincing evidence that there is no dark matter inside this ring (Van Houten 1961).

Editor's note: A gaussian fit to the ring in NGC4594 mentioned by Oort would give $R_r = 170''$, $\sigma_r = 35''$, in Roberts' notation; for a distance of 12·5 Mpc, this would correspond to $R_r = 10$ kpc, $\sigma_r = 2$ kpc.

REFERENCES

Arp, H. C. 1964, *Astrophys. J.*, **139**, 1045.
Baade, W., Arp, H. C. 1964, *Astrophys. J.*, **139**, 1027.
Dieter, N. H. 1962, *Astr. J.*, **67**, 317.
Epstein, E. E. 1964, *Astr. J.*, **69**, 521.
Roberts, M. S. 1966, *Astrophys. J.*, **144**, 639.
Seielstad, G. A., Whiteoak, J. B. 1965, *Astrophys. J.*, **142**, 616.
Van Houten, C. J. 1961, *Bull. astr. Inst. Netherl.*, **16**, 1.
Volders, L. 1959, *Bull. astr. Inst. Netherl.*, **14**, 323.

NOTE ADDED IN PROOF

For a detailed discussion of the work reported by Rougoor (p. 205), see Rogstad, D. H., Rougoor, G. W., Whiteoak, J. B. 1967, *Astrophys. J.*, in press (also in: *Obsns. Owens Valley Radio Obs.*, 1967, no. 1).

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Chapter II C

Ionized Hydrogen in Galaxies

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'De Vaucouleurs classified our Galaxy as SAB(rs)bc. If we take this to mean that we do not know how much barred the structure is, and whether there is a ring structure in the centre or not, it is probably all right.'

E. Margaret Burbidge, in Paper 36

36. IONIZED HYDROGEN IN THE GALAXY AND IN OTHER GALAXIES

(Introductory Report)

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ABSTRACT

This review summarizes data obtained by various methods, both optical (in particular: slit spectroscopy and filter photography, including interferometric techniques) and radio-astronomical (continuum studies as well as those of the recombination lines). It deals with the space distribution of H II regions, in terms of: degree of concentration to a galaxy's center, spiral pattern, layer thickness, correlation with dust, and treats their total mass and average size. It further discusses velocities of ionized hydrogen in comparison with those of neutral hydrogen, and with special attention to departures from circular motion. Finally, it considers the various determinations of electron temperature and their discrepancies. These items are discussed for both galactic and extragalactic H II regions, and distinctions are made according to galaxy type.

1. INTRODUCTION

In discussing ionized hydrogen in our own and in other galaxies, I shall exclude:

(*a*) ionized-hydrogen shells which are known to be supernova remnants from the fact that they are sources of non-thermal radio emission;

(*b*) planetary nebulae, i.e., shells of ionized gas which have been presumably ejected by one particular star, and which have to do with the evolutionary state of that star.

Thus, I shall consider that part of the interstellar matter in galaxies which has not, in the

immediate past, been part of an evolving star, but which lies close enough to massive high-temperature (young) stars or other energy sources to form H II regions.

A convenient subdivision of topics can be made if one considers all methods of observation (radio and optical) together and then discusses the material under the three headings:

distribution (see Section 2),

velocities (Section 3),

physical conditions (Section 4).

There is, of course, overlap between these headings, because velocity measures are used in computing distances which give the space distribution, and because the masses of H II regions and complexes, which fall under the first heading, are inextricably involved in determinations of physical conditions which give the electron density.

In our Galaxy, optical studies are limited by dust obscuration, while, on the contrary, in external galaxies all the information we have on the ionized gas is from *optical studies*. At the time of the 1963 symposium on galactic structure (IAU Symposium no. 20), the radio-astronomical methods of observing H II regions in the Galaxy were confined to measurements of the *continuum radiation*, in particular:

(1) observations at high frequencies, where the flat energy-frequency spectrum of thermal radiation produced by free-free emission causes this radiation to dominate over the falling energy-frequency spectrum of non-thermal radio emission produced by the synchrotron process;

(2) observations at low frequencies, in the region where free-free absorption processes occurring over the underlying synchrotron spectrum become apparent.

Since that date, a very important new method has become available, whereby line-of-sight velocities in distant and optically obscured as well as in nearby H II regions can be measured, namely, the observation of the so-called *recombination lines*, corresponding to transitions between very high energy-levels in hydrogen, with energy differences lying in the radio-frequency region. Such transitions had at one time been thought to be of no practical interest, as they would merely blur into one another and form an unrecognizable addition to the continuum radiation (Wild 1952). But Kardašev (1959) realized that the transitions $n + 1 \rightarrow n$ would dominate in intensity for any series with the lower level n, so that these lines should stand out and be observable in H II regions with a sufficiently large emission measure. The observation of such lines was first made by Z. V. Dravskih, A. F. Dravskih, and V. A. Kolbasov at Pulkovo, and also by R. L. Soročenko and E. V. Borodzič, and announced at the Twelfth General Assembly of the IAU at Hamburg in 1964 (see also Dravskih and Dravskih 1964), but results pertaining to galactic structure or dynamics were not yet available.

Since then, the 109α line at 5008·9 MHz was detected by Höglund and Mezger (1965), the 156α and 158α lines by Lilley *et al.* (1966*a*), and the 166α line by Palmer and Zuckerman (1966); we adopt the notation suggested by Palmer and Zuckerman. Mrs Dieter (1967; see Paper 39 in this volume) has observed the 158α line at 1651 MHz. Recently, Mezger and Höglund (1967; see also Paper 38 in this volume) have measured and analyzed the line-of-sight velocities in a number of thermal radio sources. This line radiation presents a definitive method, in cases where radio spectra have not led to a certain separation between thermal and non-thermal sources, of deciding which sources

emit thermal radiation. Further, Lilley *et al.* (1966*b*) have observed the 156α, 158α, and 159α helium lines, from the recombination of He^{++} to He^{+}, thus opening the way to determinations of the He/H abundance ratio.

2. DISTRIBUTION AND MASS OF IONIZED HYDROGEN; DIMENSIONS OF H II REGIONS

a. Distribution from optical studies

In *our own Galaxy* bright nebulae have been catalogued from plates taken in the red and blue (a combination which enables true emission nebulae to be separated from reflection nebulae), or from plates taken through narrow Hα filters. Courtès has used filters only 4 or 6 Å wide, and this increases the contrast of H II regions against the dense stellar background, so that one can find emission regions which do not show on the red Palomar Sky Survey plates at all.

From the Palomar Sky Survey plates Mrs Lynds (1965) has compiled a new catalogue of emission nebulae, going to declination $-33°$, with 1125 entries, which is more extensive than the earlier catalogue by Sharpless (1959). Both surveys include supernova remnants in the count. For the southern hemisphere there is the catalogue by Rodgers *et al.* (1960*a*) and the Mount Stromlo Atlas by Rodgers *et al.* (1960*b*). In Mrs Lynds's catalogue the total area covered by bright nebulae whose red color indicates them to be H II regions is 781 square degrees, or around 1/40 of the area surveyed.

The location of individual H II regions in the Galaxy and the tracing of spiral arms by them has been a matter of extending and refining the method used by Morgan and his collaborators (1953), and applied in the southern hemisphere by Bok and others (e.g. the I Sco association at 1800 pc distance: Bok *et al.* 1966), and by the Pretoria workers. Accounts and bibliographies have been given by Sharpless (1965), Becker (1964*a*) and Bok (1964). Becker (1964*b*) plotted the distribution of H II regions in three spiral arms, and showed these superposed on the external galaxy NGC 1232. The latter is an Sc spiral (Sandage 1961) whose outer arms resemble what appears to be the arrangement in our Galaxy.

The distribution of H II regions *in other galaxies* can be mapped optically by long-slit spectra taken with the slit set in various orientations across the galaxy; this method gives a general though incomplete picture of the distribution in the whole galaxy, but at the same time it yields line-of-sight velocities and, if calibrated, line intensities. Alternatively, the H II distribution can be mapped throughout the galaxy by means of photographs through Hα filters, which can also be calibrated for photometric analysis. For the Magellanic Clouds, objective-prism plates have been used to map H II regions and to study them photometrically (Henize, 1956; Doherty, Henize, and Aller 1956).

Mayall (1958) has derived distributions from *slit spectra* of the [O II] $\lambda 3727$ emission, which is characteristic of H II regions as is also [N II] $\lambda 6583$, since the first ionization potential of oxygen and that of hydrogen are almost exactly the same, and that of nitrogen is only slightly higher. Mayall found a correlation between the occurrence of $\lambda 3727$ emission and nebular type, and noted that in the 15% of ellipticals where emission is observed, it is always strongly concentrated to the center, while it is seen with increasing frequency and decreasing central condensation along the Hubble sequence. Osterbrock (1960, 1962) studied the occurrence of [O II] in the centers of elliptical and So galaxies.

Burbidge and Burbidge (1962, 1965; see also E. M. Burbidge 1962) used the Hα and [N II] lines to study gas in spirals and irregulars, and in elliptical and So galaxies, respectively. Throughout the irregulars H II regions occur, with no concentration towards the nucleus (if present at all), while there is, on the average, a tendency for an increasing degree of central concentration as one goes along the morphological sequence, as found by Mayall (1958). In most Sc galaxies and in a good proportion of Sb galaxies the H II regions right in the nuclei are similar to those found in the spiral arms. In a few Sc galaxies, some Sb's, most Sa and So systems, and virtually all ellipticals, however, there is a distinct difference to which I shall return in Section 4.

Courtès has applied *filter photography*, particularly with interference filters of very narrow passbands, to a number of galaxies, e.g. M33 (Courtès and Cruvellier 1965), NGC4258 and 1275 (Courtès *et al.* 1963), and the Magellanic Clouds (Courtès 1964). His studies by means of Fabry-Pérot interference spectra, which give velocities and hence should properly be considered under Section 3, also give information on the distribution of ionized hydrogen. Butslov *et al.* (1962), using an image tube, have also made such photographs of a number of external galaxies, and Véron and Sauvayre (1965) have studied the galaxies NGC2403, 2903 and 4490 in Hα light.

When very narrow-band filters are employed, such as that of 4Å width used by Courtès, one has to take account of the rotation of the galaxy, as well as its redshift, because 1Å corresponds to 45 km/sec at the Hα line. If a wider bandpass is used, [N II] emission will be included with the Hα line.

Sometimes regions are found, outside the nucleus of a galaxy, where there is Hα emission but no evidence for exciting blue O or B stars imbedded in it. There is one such region, found by Courtès and Cruvellier (1965), in M33. It is quite close to the nucleus and it might, of course, be a supernova remnant. A much larger feature was found by Courtès in NGC4258, and it is of great interest in our attempts to understand the processes going on in galaxies. The system NGC4258 has some of the characteristics of a barred spiral, and non-circular motions have been found in one of its arms (Burbidge *et al.* 1963*a*). In his Hα interference-filter photograph, Courtès found a strange arm of Hα emission coming from the nuclear region with a branched structure; it did not appear on the blue photographs, so there was no evidence for a concentration of blue stars to produce the ionization. Courtès considers that this rather large-scale feature may be connected with activity in the nucleus of this galaxy. In M33 and in the Magellanic Clouds, Courtès and his colleagues have found a general Hα emission extending in M33 up to 3 kpc from the center.

In M31 the angular diameter is large enough so that individual H II regions can be mapped out in detail (Baade and Arp 1964). In a nearly face-on galaxy like NGC1232 the shape of the spiral arms can be very well seen, but the *thickness* of the H II layer and the extent of coplanarity of the arms cannot be determined. On the other hand, in an edge-on spiral like NGC4565 or NGC891 (the latter was picked by Baade (1958) as being similar to our own, as judged by the wide-angle photographs of the Milky Way taken by Sharpless and Osterbrock (1952)) one can determine the thickness of the H II layer but not the *shape* of the spiral arms. In M31 Arp (1964) used the observed distribution of H II regions in an attempt to reconstruct a face-on picture of the galaxy. The H II regions lie mainly between 8 and 14 kpc from the center, but the best interpretation was that they were not coplanar throughout, the departure amounting to 5°. That the inner spiral structure in M31, which is delineated by dust arms, may not be coplanar

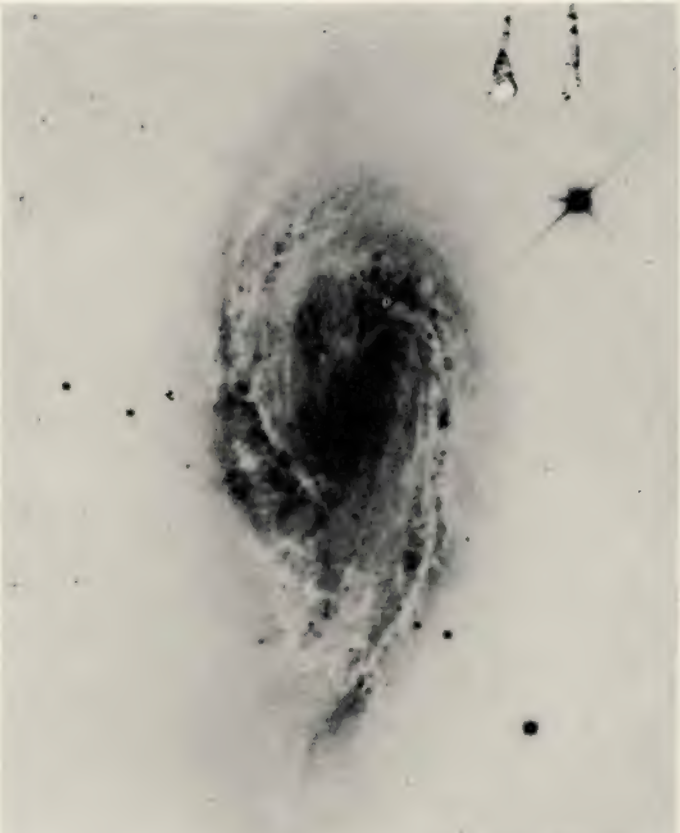

FIG. 1. NGC 3627, photographed at prime focus of McDonald 82-inch telescope. North is at top, east at left. This galaxy contains much ionized gas as well as prominent dust lanes. Notice that spiral arms appear as though non-coplanar.

FIG. 2. NGC4826, photographed at prime focus of Lick 120-inch telescope. West is at top, north at right. Notice unusual wave structure in dust lanes at east end of galaxy, and 'crossing-arm' structure at north-west. Dusty regions are also H II regions.

with the outer arms, had already been noted by Baade (1958). Figure 1 illustrates the system NGC3627, which is very rich in H II regions. The spiral arms in this galaxy strongly suggest non-coplanarity.

There is one final point concerning the overall distribution of H II regions in galaxies: one finds quite commonly that regions appearing dark in blue integrated light, i.e., very *dusty areas, have quite strong* H α *emission* in them; in other words, ionized hydrogen and dust are either coexistent or well intermingled. NGC5128 is a good example, and so is NGC4826 (Figure 2) with its prominent dust lanes. The presence of dust in the nuclei of So and E galaxies has been strongly suggested by the excess reddening measured there (Wood 1966), but no [O II] emission has been seen in the few galaxies for which these measures exist. In our own Galaxy, O'Dell *et al.* (1966) have shown dust to be present in bright emission nebulae, but also there seem to be weaker H II emission nebulae which appear as such on the red Sky Atlas plates but as dark nebulae (i.e. dusty regions) on the blue plates (B. T. Lynds 1965).

Another way of mapping the H II distribution in our Galaxy is to make a surface photometry of the Milky Way, but, as Isserstedt and Schmidt-Kaler (1964) have shown, one must map also the color excess and hence the extinction by means of objects of known distance, since regions which appear as intensity maxima that might be interpreted as directions where the line of sight runs tangential to a spiral arm (cf. the radio surveys), may actually merely be regions of minimum dust and hence maximum transparency. The only way to avoid this confusion is by a knowledge of the distribution of color excess.

b. Distribution from radio-astronomical measures

As already mentioned, low- or high-frequency measures are best suited for studying galactic structure. Earlier reviews of this subject are due to Komesaroff and Westerhout (1964), to Mills (1964), and to Kerr and Westerhout (1965). Distances of thermal radio sources could formerly be obtained either by measuring angular dimensions or by studying the line profiles of 21-cm absorption due to neutral hydrogen in the foreground. Most recently a third method has become available, similar to that used for studies of the distribution of neutral hydrogen: measuring line-of-sight velocities in the high-order recombination lines and placing the gas by means of an adopted rotation curve for the Galaxy. Akabane and Kerr (1965) estimated the distant strong thermal source, W49, to be 15 kpc from the Sun, and Mezger and Höglund (1967), from measurements of the 109α line in this source, have obtained a similar result. This is a strong emitter, with an intrinsic output some 300 times that of the Orion Nebula, or 1/4 that of the 30 Doradus Nebula.

One can infer general structure of the Galaxy from measurements of the positions of steps in intensity; the high intensities are then interpreted as being seen in directions in which one looks tangential to spiral arms.

Apart from the spiral-arm structure, Westerhout (1958*a*) deduced a maximum density of ionized hydrogen in a ring some 4 kpc from the center (see also Mathewson *et al.* 1962), and showed that the regions of higher density appear to be very closely concentrated to the plane of the Galaxy, with a weaker general distribution similar to that of neutral hydrogen.

Recently, high-resolution surveys at high frequencies have been undertaken, and one sees a great deal of structure in regions that are strong thermal emitters. Examples are

studies of the Cygnus-X region by Pike and Drake (1964) and by Downes and Rinehart (1966). Véron (1965) has shown that the OB association VI Cyg, 1500 pc distant, is probably the source of excitation in this emission region. The complex source W22 (NGC6357) has been studied by Mrs Heidmann (1965). RaghavaRao *et al.* (1965) have studied the Cassiopeia and Cepheus regions.

The nuclear region of the Galaxy is the subject of a separate session (Chapter IIIC). For comparison with external galaxies, we may mention that there is plenty of ionized hydrogen in our nucleus; Lequeux (Paper 68) estimates a total of some $8 \times 10^5 M_\odot$, i.e., an average electron density of about 10 cm^{-3} spread over 100 pc radius.

c. Mass of ionized hydrogen in galaxies

For our Galaxy, we have Westerhout's (1958*b*) estimate of $4 \times 10^7 M_\odot$, which had a large uncertainty factor (Komesaroff and Westerhout 1964). Hoyle and Ellis (1963) made an estimate, based on the maximum in the radio spectrum around 5 MHz (derived both from the Tasmania ground-based observations and from measures made above the atmosphere). If the turnover in the spectrum is due to absorption by ionized hydrogen, fairly smoothly distributed in a layer of half-width 300 pc and average electron density $0{\cdot}1 \text{ cm}^{-3}$, the total mass of ionized gas turns out to be $5 \times 10^8 M_\odot$, which (in view of the uncertainties) is not in disagreement with Westerhout's value.

For other galaxies one may do photometry in Hα radiation, but so far the only studies I know of are those by Lynds and Sandage (1963) and by Courtès *et al.* (1967) for the irregular radio galaxy M82. For the gas in the filamentary structure emitting Hα, which they presume to have been ejected by a central explosive event, Lynds and Sandage estimated a mass of $5{\cdot}8 \times 10^6 M_\odot$, or 2×10^{-4} times the total mass of the galaxy, while Courtès *et al.* estimated a mass about twice this value. Since the object is seen nearly edge-on, the true mass of ionized hydrogen throughout the galaxy must be considerably larger than this. This method could be applied very well to more nearly face-on galaxies such as M51.

The only estimate of the mass of ionized gas present in an elliptical system is that made by Osterbrock (1960) for NGC4278. He concluded that this mass is in the range 10^4 to $10^6 M_\odot$. However, it was only possible to make this estimate because the nucleus has a rich emission-line spectrum, and in this sense it is an unusual elliptical system.

d. Sizes of H II *regions*

There has been considerable interest in measuring the sizes of H II regions in external galaxies, since they can possibly be used as distance indicators (Sandage 1958). Using measures by Sérsic (1960), Sandage (1962) has given 265 and 228 pc for the sizes of the largest H II regions in M33 and in the Large Magellanic Cloud, respectively. The mean diameter of the five largest H II regions in these galaxies is 211 and 145 pc, respectively. Sérsic (1960) has done an extensive study of H II regions in 66 galaxies, and he finds that their sizes vary with galactic type, the mean of the three largest regions being as follows:

Type	Sa	Sb⁻	Sb⁺	Sc⁻	Sc⁺	Ir I	dSc
D (pc)	60	90	140	180	145	110	70

The trend of sizes is in the sense that the dimensions increase with increasing neutral-hydrogen content (relative to the total mass), until one reaches the irregular and dwarf-Sc

FIG. 3. NGC6181, photographed at prime focus of Lick 120-inch telescope, in blue light (baked Kodak IIa-O emulsion, no filter). Inset: darker print from same plate, showing structure in center. North is at top, east at left. Scale: 1 mm = 1″2. Notice 'crossing-arm' structure at south-east end of main body; the velocity 'bump' illustrated in Figure 4 occurs here. (Burbidge *et al.* 1965)

galaxies, where the falling-off in size is probably connected with the fact that these systems have less mass. Courtès and Cruvellier (1965) carried out a study of M33. They found for the sizes of H II regions a frequency maximum at about 35 pc, with a distribution function in agreement with that found by Sandage.

Sérsic (1964) has tried to relate these sizes with current ideas on the formation of stars out of interstellar material. He did this by relating the fraction of space filled with ionized gas to the rate of formation of massive stars, using the formulation of Salpeter (1959) and Schmidt (1959, 1963), where the formation rate is proportional to the first or second power of the gas density. He has then applied this relation to interpret the frequency function of the diameters of H II regions in various galaxies. While this work is necessarily of a preliminary character, the results are consistent with current ideas on star formation.

3. VELOCITIES

Velocities of H II regions in our Galaxy have been measured from slit spectrograms and by other methods. Courtès *et al.* (1966) have studied 180 H II regions following the Fabry-Pérot interference-fringe method; some of their results are summarized by Courtès in Paper 37 in this volume. Recently Mezger and Höglund (1967) have begun to measure velocities by radio-astronomical methods, using the 109α line; their results are in excellent agreement with the optical measures of Courtès *et al.* In external galaxies the methods of slit spectroscopy have mostly been followed. In the Magellanic Clouds there are comparisons available between velocities of neutral hydrogen, measured at 21 cm, and optical velocities of H II regions (Bok *et al.* 1964, Courtès 1964, Feast 1964, McGee 1964), and there is good agreement. In the Large Magellanic Cloud, the average difference between neutral and ionized gas is only $+1{\cdot}3 \pm 6{\cdot}4$ km/sec.

For our own Galaxy Courtès (1959; see also Paper 37 in this volume) has shown that in the Perseus Arm the velocities agree well with those expected if only circular motion is occurring. In the Sagittarius Arm there are departures by 15 km/sec from circular motion, and these are similar to those found in the 21-cm studies in the same region (Shane, Paper 29 in this volume). Following the work of Courtès and Cruvellier (1960), Georgelin and Monnet have demonstrated a large departure, of about -200 km/sec, from the velocity expected on the assumption of circular motion, at positions within 1° in l and b from the center; one might here be looking at the edge of the nuclear region that gives large negative velocities in the 21-cm measures.

Most of the mass determinations for spiral galaxies have been obtained by measuring emission lines produced in H II regions, and hence by determining the rotation curves of ionized gas in these galaxies. Early work was done by Babcock, Mayall, Aller, and others on M31 and M33. Since 1958 my colleagues and myself have carried out fairly extensive investigations on a variety of galaxies, using the long-slit technique; and others have also contributed. In many cases we have found *departures from circular motion.* High velocities in the nuclei of galaxies are not an uncommon feature, especially in the barred spirals. A particularly good case is NGC1097, which has a ring of fast-rotating ionized gas within about 2 kpc of the center, with a velocity difference from one side to the other of more than 400 km/sec (Burbidge and Burbidge 1960). There are fast-moving H II regions in the nuclei of NGC1365 and NGC5383, which are also barred spirals, and in these objects there is clear-cut evidence for departures from circular motion (Burbidge

et al. 1962*a*, 1962*b*). In NGC 1365, it appears that the results cannot be explained either in terms of uniform axi-symmetric radial expansion.

In M 31 Münch (1960) has detected non-circular motions in the central region, which indicate an outflow of gas. In M 51, Burbidge and Burbidge (1964) have shown that there is a very complex pattern of motions in the central part, with large departures from circular motion, of the order of 100 km/sec, within about 600 pc from the center, and again the measures do not indicate uniform radial outflow but rather a directed outflow. This system is illustrated in Figure 5.

In the spiral galaxies NGC 2903, NGC 4258 and NGC 6181 (Burbidge *et al.* 1960, 1963*a*, 1965) we have found evidence for departures from circular motion in large H II complexes well outside the nuclear regions of these galaxies. NGC 6181 (Figure 3) is intermediate between a barred and an ordinary spiral galaxy. The H II velocities (Figure 4) are in general characteristic of a normal rotation curve, but there is a disturbance giving a velocity peak at a point where the spectrograph slit crosses the inner edge of a strong dark lane. More detailed work is needed so that complete maps of the velocity field can be constructed, as a preliminary to understanding the dynamics of the ionized gas.

A detailed study of a large number of H II regions in M 33 has been made by Brandt (1965), who has found departures of velocities from circular motion ranging up to 30 or 40 km/sec, the r.m.s. value being 10 km/sec. There is no trend with distance from the center in these motions. Carranza *et al.* (1967) have recently used the optical interference

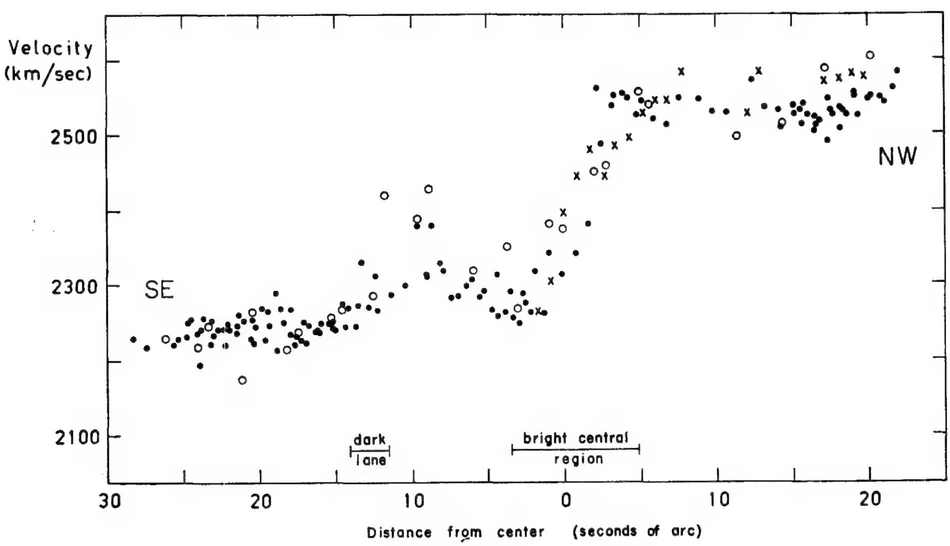

FIG. 4. Measured velocities, relative to local standard of rest but uncorrected for rotation of our Galaxy, in NGC 6181 in position angle 153°.
Dots: emission lines of [O II], Hγ, and Hδ from Lick spectrogram;
crosses: absorption line of Ca II λ3934 from same spectrogram;
open circles: emission lines of Hα and [N II] λ6583 from McDonald spectrogram. (Burbidge *et al.* 1965)

FIG. 5. M 51 and companion NGC 5195, photographed in blue light (103a–O plate, no filter) at prime focus of Lick 120-inch telescope by N. U. Mayall. North is at top, east at left. Scale: 1 mm = 4.″2. A velocity 'bump' occurs in south-west quadrant of nuclear region (overexposed on this plate), about 5″ from center. (Burbidge and Burbidge 1964)

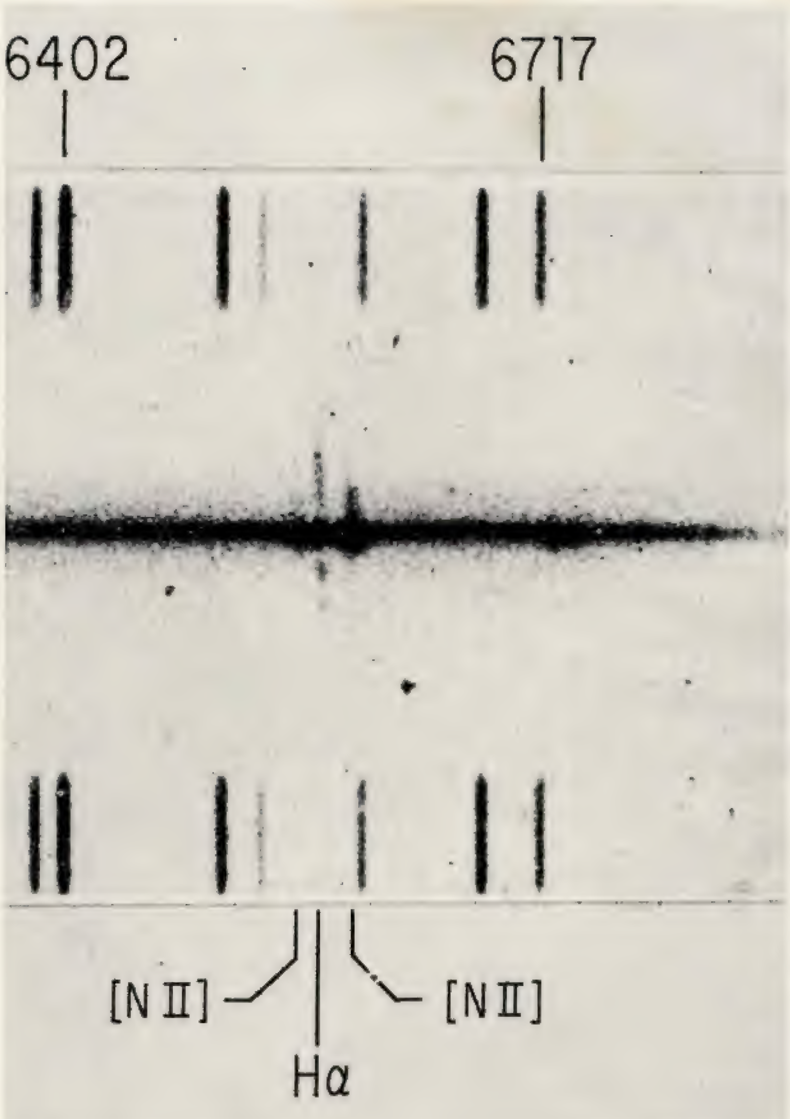

FIG. 6. Spectrogram of nuclear region of M 51 taken with Lick prime-focus spectrograph, showing Hα and [N II] emission lines within 10″–15″ of center, in position angle 171°. Wavelengths of two neon comparison lines marked at top. Notice change in relative intensity of Hα and [N II], on going in to very center of galaxy. [S II] λλ6716, 6731 can also be seen in nucleus. (Burbidge *et al.* 1963*b*)

method of measurement of the H α line for a detailed study of M 33, and found a dispersion in velocity similar to that found by Brandt; the dispersion is rather small between 0·15 and 0·50 kpc from the center and increases to ± 30 km/sec with the beginning of the spiral structure; see also Paper 37, Figure 5.

4. PHYSICAL CONDITIONS IN H II REGIONS

Estimates of the electron density, n_e, and the electron temperature, T_e, can be made by measuring the ratios of the strengths of some of the emission lines, and by measuring the strengths of the Balmer lines relative to the continuum.

Osterbrock and Seaton have shown that n_e can be estimated from the relative intensities of the two components in the [O II] $\lambda 3727$ doublet. In regions where the velocity dispersion is high, as for example in the centers of elliptical galaxies, so that the two components are blended together, estimates of the relative intensities can be made by measuring the mean wavelength of the blend. To obtain T_e one can use the ratio of the forbidden-line strengths. The most accurate determinations come from the ratio of the [O III] lines $\lambda\lambda 5007$, 4959 to $\lambda 4363$. However, this method is only applicable if the temperature is high enough so that there is plenty of O^{++}. If the lines whose ratio is required are widely separated, or if one measures the Balmer lines relative to the Balmer continuum, there is a serious problem stemming from differential reddening. A considerable amount of detailed work has been done on ionized regions following these methods, particularly by Seaton, Osterbrock, Aller, O'Dell and their colleagues. However, their work has been largely oriented to study of planetary nebulae and other, rather special, ionized-hydrogen regions such as the Orion Nebula, where the level of excitation is fairly high and the density is above average so that a rich emission spectrum is seen. In the extended H II regions, which are widespread in the spiral arms of galaxies, the only observable lines normally are [O II] $\lambda 3727$, H α $\lambda 6563$, and [N II] $\lambda\lambda 6548$, 6583. The ratio of H α to the [N II] doublet can serve for a simple investigation into the excitation conditions on the large scale in galaxies, and these lines are close together so differential reddening does not pose a problem. However, this intensity ratio depends on the relative abundances of N and H, and on the degree of ionization. The temperatures indicated by the H α/[N II] ratio in widespread, extended H II regions in external galaxies are around 6000° for a normal abundance ratio and equal degrees of ionization of H and N (Burbidge *et al.* 1963*b*).

Following the work of Kardašev (1959), there have been determinations of T_e in H II regions from the radio-frequency *recombination lines* of hydrogen (Höglund and Mezger 1965; Lilley *et al.* 1966; Palmer and Zuckerman 1966; Mezger and Höglund 1967; see also Mezger, Paper 38, and Dieter, Paper 39 in this volume). The values derived have been around 5000°, considerably lower than those determined from optical measures of [O III] lines. The radio-astronomical determinations have been criticized by Goldberg (1966), who pointed out that a substantial part of this line radiation is stimulated emission. The population factors, b_n, by which the actual population of a level n differs from the thermal-equilibrium population, are of course close to unity for large n, but they do actually have a positive gradient with respect to n, so that at large n, b_n increases with n. This may lead to an enhancement of the line intensities through a kind of maser action, and thus it may not be valid to use the line intensities for determining T_e. This subject is a controversial one at present.

The general balance between heating and cooling mechanisms in ionized gas (Burbidge

et al. 1963*b*) also led to a somewhat lower T_e than that obtained in bright H II regions from the line intensities, but Osterbrock (1965) has reconsidered these processes in the light of a smaller collisional-excitation parameter for the Ne^+ ions than the earlier authors had used. Since Ne^+ ions had been taken as the principal cooling agent, Osterbrock obtained somewhat higher electron temperatures, in the range 7000 to 9000 °K, as the equilibrium values to be expected around stars of temperatures between 50 000 and 100 000 °K.

Concerning the electron temperatures, there is one further interesting feature of the nuclei of galaxies. The relative intensities of the emission lines, Hα λ6563 and [N II] λ6583, sometimes change markedly on going from the spiral-arm regions of a galaxy, where this ratio is about 3, to the nuclear region, where it can be very much less than unity (Burbidge and Burbidge 1962). This effect is seen very well in the nucleus of M 51 (Figure 6). A survey of many emission nebulosities in our Galaxy by Courtès (1960) is very interesting in this respect. He used the reducing camera with a Fabry-Pérot etalon, and listed the H II regions in three groups, with intensity ratios [N II]/Hα greater than, equal to, and less than 0·3. Radial velocities and internal velocities were measured in this study, but here we are concerned with the line intensities. The ratio Hα/[N II] can become large in high-density H II regions, where collisional de-excitation reduces the [N II] emission, but it can only become small if T_e is high or, conceivably, if the abundance ratio N/H is unusually high.

Burbidge *et al.* (1963*b*) took the view that in galaxies there is likely to be an effective mixing of the gas, so that abundance anomalies, even in the nuclei, where the density of evolving stars is large, would not be expected to be established. Then one finds that values of T_e of 15 000 or 20 000 °K are needed to give the low values of Hα/[N II] found in nuclei. This phenomenon is strongly correlated with morphological type; for 85 galaxies surveyed by Burbidge and Burbidge (1965), the ratio Hα/[N II] λ6583 is $\leqslant 1$ in 100% of the ellipticals, 81% of the So's, 55% of the spirals, and 0% of the irregulars. Thus, in all the irregulars and in about half the spirals, the ratio has the normal spiral-arm value. It was suggested that the high T_e needed to explain the effect in the K-type nuclei might be produced by enhanced 'stellar-wind' effects from the surfaces of K-type giant stars.

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REFERENCES

Akabane, K., Kerr, F. J. 1965, *Austr. J. Phys.*, **18**, 91.
Arp, H. C. 1964, *Astrophys. J.*, **139**, 1045.
Baade, W. 1958, IAU Symposium, no. 5, *Comparison of the Large-Scale Structure of the Galactic System with that of Other Stellar Systems*, Ed. N. G. Roman, p. 1, Cambridge Univ. Press, Cambridge.
Baade, W., Arp, H. C. 1964, *Astrophys. J.*, **139**, 1027.
Becker, W. 1964*a*, IAU Symposium, no. 20, *The Galaxy and the Magellanic Clouds*, Eds. F. J. Kerr and A. W. Rodgers, p. 16, Austr. Acad. Sci., Canberra.
Becker, W. 1964*b*, *Z. Astrophys.*, **58**, 202.
Bok, B. J. 1964, IAU Symposium no. 20, *The Galaxy and the Magellanic Clouds*, Eds. F. J. Kerr and A. W. Rodgers, p. 147, Austr. Acad. Sci., Canberra.
Bok, B. J., Gollnow, H., Hindman, J. V., Mowat, M. 1964, *Austr. J. Phys.*, **17**, 404.

Bok, B. J., Bok, P. F., Graham, J. A. 1966, *Mon. Not. R. astr. Soc.*, **131**, 247.
Brandt, J. C. 1965, *Mon. Not. R. astr. Soc.*, **129**, 309.
Burbidge, E. M. 1962, in *The Distribution and Motion of Interstellar Matter in Galaxies*, Ed. L. Woltjer, W. A. Benjamin, Inc., New York, p. 123.
Burbidge, E. M., Burbidge, G. R. 1960, *Astrophys. J.*, **132**, 30.
Burbidge, E. M., Burbidge, G. R. 1962, *Astrophys. J.*, **135**, 694.
Burbidge, E. M., Burbidge, G. R. 1964, *Astrophys. J.*, **140**, 1445.
Burbidge, E. M., Burbidge, G. R. 1965, *Astrophys. J.*, **142**, 634.
Burbidge, E. M., Burbidge, G. R., Prendergast, K. H. 1960, *Astrophys. J.*, **132**, 640.
Burbidge, E. M., Burbidge, G. R., Prendergast, K. H. 1962*a*, *Astrophys. J.*, **136**, 119.
Burbidge, E. M., Burbidge, G. R., Prendergast, K. H. 1962*b*, *Astrophys. J.*, **136**, 704.
Burbidge, E. M., Burbidge, G. R., Prendergast, K. H. 1963*a*, *Astrophys. J.*, **138**, 375.
Burbidge, E. M., Burbidge, G. R., Prendergast, K. H. 1965, *Astrophys. J.*, **142**, 641.
Burbidge, G. R., Gould, R. J., Pottasch, S. R. 1963*b*, *Astrophys. J.*, **138**, 945.
Butslov, M. M., Kopylov, I. M., Nikonov, V. B., Severnyj, A. B., Čuvaev, K. K. 1962, *Astr. Zu.*, **39**, 315 (translation in 1962, *Soviet Astr.*, **6**, 244).
Carranza, G., Courtès, G., Georgelin, Y., Monnet, G. 1967, *C. r. hebd. Séanc. Acad. Sci.*, Paris, **264**, Se'r. B, 191.
Courtès, G. 1959, *C. r. hebd. Séanc. Acad. Sci.*, Paris, **248**, 2953 = *Publ. Obs. Hte-Provence*, **4**, no. 44.
Courtès, G. 1960, *Ann. Astrophys.*, **23**, 115.
Courtès, G. 1964, IAU Symposium, no. 20, *The Galaxy and the Magellanic Clouds*, Eds. F. J. Kerr and A. W. Rodgers, p. 278, Austr. Acad. Sci., Canberra.
Courtès, G., Cruvellier, P. 1960, *C. r. hebd. Séanc. Acad. Sci.*, Paris, **251**, 2470 = *Publ. Obs. Hte-Provence*, **5**, no. 26.
Courtès, G., Cruvellier, P. 1965, *Ann. Astrophys.*, **28**, 683.
Courtès, G., Viton, M., Véron, P. 1963, in *Quasi-Stellar Sources and Gravitational Collapse*, Eds. I. Robinson, A. Schild and E. L. Schucking, Univ. of Chicago Press, Chicago, p. 307.
Courtès, G., Cruvellier, P., Georgelin, Y. 1966, *J. Observateurs*, Marseille, **49**, 329.
Courtès, G., Monnet, G. J., Pellet, A. 1967, IAU Symposium, no. 29, *Instability Phenomena in Galaxies* (in press).
Dieter, N. H. 1967, *Astrophys. J.*, in press.
Doherty, L., Henize, K. G., Aller, L. H. 1956, *Astrophys. J. Suppl. Ser.*, **2**, 345.
Downes, D., Rinehart, R. 1966, *Astrophys. J.*, **144**, 937.
Dravskih, Z. V., Dravskih, A. F. 1964, *Astr. Cirk. Izdav. bjuro astr. Soobšč. Kazan*, no. 282, 2.
Feast, M. W. 1964, *Mon. Not. R. astr. Soc.*, **127**, 195.
Goldberg, L. 1966, *Astrophys. J.*, **144**, 1225.
Heidmann, N. 1965, *Ann. Astrophys.*, **28**, 521.
Henize, K. G. 1956, *Astrophys. J. Suppl. Ser.*, **2**, 315.
Höglund, B., Mezger, P. G. 1965, *Science*, **150**, 339.
Hoyle, F., Ellis, G. R. A. 1963, *Austr. J. Phys.*, **16**, 1.
Isserstedt, J., Schmidt-Kaler, Th. 1964, *Z. Astrophys.*, **59**, 182.
Kardašev, N. S. 1959, *Astr. Zu.*, **36**, 838 (translation in 1960, *Soviet Astr.*, **3**, 813).
Kerr, F. J., Westerhout, G. 1965, in *Galactic Structure*, Eds. A. Blaauw and M. Schmidt, Vol. V in the series: *Stars and Stellar Systems*, Univ. of Chicago Press, Chicago, p. 167.
Komesaroff, M. M., Westerhout, G. 1964, IAU Symposium, no. 20, *The Galaxy and the Magellanic Clouds*, Eds. F. J. Kerr and A. W. Rodgers, p. 116, Austr. Acad. Sci., Canberra.
Lilley, A. E., Menzel, D. H., Penfield, H., Zuckerman, B. 1966*a*, *Nature*, **209**, 468.
Lilley, A. E., Palmer, P., Penfield, H., Zuckerman, B. 1966*b*, *Nature*, **211**, 174.
Lynds, B. T. 1965, *Astrophys. J. Suppl. Ser.*, **12**, 163.

Lynds, C. R., Sandage, A. R. 1963, *Astrophys. J.*, **137**, 1005.
Mathewson, D. S., Healey, J. R., Rome, J. M. 1962, *Austr. J. Phys.*, **15**, 354.
Mayall, N. U. 1958, IAU Symposium, no. 5, *Comparison of the Large-Scale Structure of the Galactic System with that of Other Stellar Systems*, Ed. N. G. Roman, p. 23, Cambridge Univ. Press, Cambridge.
McGee, R. X. 1964, *Austr. J. Phys.*, **17**, 515.
Mezger, P. G., Höglund, B. 1967, *Astrophys. J.*, **147**, 490.
Mills, B. Y. 1964, IAU Symposium, no. 20, *The Galaxy and the Magellanic Clouds*, Eds. F. J. Kerr and A. W. Rodgers, p. 102, Austr. Acad. Sci., Canberra.
Morgan, W. W., Whitford, A. E., Code, A. D. 1953, *Astrophys. J.*, **118**, 318.
Münch, G. 1960, *Astrophys. J.*, **131**, 250.
O'Dell, C. R., Hubbard, W. B., Peimbert, M. 1966, *Astrophys. J.*, **143**, 743.
Osterbrock, D. E. 1960, *Astrophys. J.*, **132**, 325.
Osterbrock, D. E. 1962, in *The Distribution and Motion of Interstellar Matter in Galaxies*, Ed. L. Woltjer, W. A. Benjamin, Inc., New York, p. 111.
Osterbrock, D. E. 1965, *Astrophys. J.*, **142**, 1423.
Palmer, P., Zuckerman, B. 1966, *Nature*, **209**, 1118.
Pike, E. M., Drake, F. D. 1964, *Astrophys. J.*, **139**, 545.
RaghavaRao, R., Medd, W. J., Higgs, L. A., Broten, N. W. 1965, *Mon. Not. R. astr. Soc.*, **129**, 159.
Rodgers, A. W., Campbell, C. T., Whiteoak, J. B. 1960*a*, *Mon. Not. R. astr. Soc.*, **121**, 103.
Rodgers, A. W., Campbell, C. T., Whiteoak, J. B., Bailey, H. H., Hunt, V. O. 1960*b*, *An Atlas of H-alpha Emission in the Southern Milky Way*, Mt. Stromlo Obs., Canberra.
Salpeter, E. E. 1959, *Astrophys. J.*, **129**, 608.
Sandage, A. R. 1958, *Astrophys. J.*, **127**, 513.
Sandage, A. R. 1961, *The Hubble Atlas of Galaxies*, Carnegie Instn. of Washington, Washington, D.C.
Sandage, A. R. 1962, IAU Symposium, no. 15, *Problems of Extra-Galactic Research*, Ed. G. C. McVittie, p. 359, The MacMillan Company, New York.
Schmidt, M. 1959, *Astrophys. J.*, **129**, 243.
Schmidt, M. 1963, *Astrophys. J.*, **137**, 758.
Sérsic, J. L. 1960, *Z. Astrophys.*, **50**, 168.
Sérsic, J. L. 1964, *Z. Astrophys.*, **58**, 259.
Sharpless, S. 1959, *Astrophys. J. Suppl. Ser.*, **4**, 257.
Sharpless, S. 1965, in *Galactic Structure*, Eds. A. Blaauw and M. Schmidt, Vol. V in the series: *Stars and Stellar Systems*, Univ. of Chicago Press, Chicago, p. 131.
Sharpless, S., Osterbrock, D. E. 1952, *Astrophys. J.*, **115**, 89.
Véron, P. 1965, *Ann. Astrophys.*, **28**, 391.
Véron, P., Sauvayre, A. 1965, *Ann. Astrophys.*, **28**, 698.
Westerhout, G. 1958*a*, *Bull. astr. Inst. Netherl.*, **14**, 215.
Westerhout, G. 1958*b*, *Bull. astr. Inst. Netherl.*, **14**, 261.
Wild, J. P. 1952, *Astrophys. J.*, **115**, 206.
Wood, D. B. 1966, *Astrophys. J.*, **145**, 36.

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37. INTERFEROMETRIC STUDIES OF H II REGIONS

(Invited Paper)

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ABSTRACT

The paper briefly summarizes the application of interference techniques to studies of structure and kinematics both of our Galaxy and of the nearest external galaxies.

Since the principal results of our work have been published elsewhere (Courtès 1960, Courtès *et al.* 1966), we shall restrict ourselves here to a brief summary of the most important points, especially those related to radio-astronomical investigations.

1. GALACTIC STUDIES

a. Physics of H II *regions*

By means of interference techniques, we have obtained quantitative measurements of Hα profiles with a resolving power of 5×10^4. The instrumental profile was checked with the [N II] line at 6584Å, which is very close in wavelength to Hα while the atomic weights are sufficiently different that one can observe the ratio of profile widths of the two lines.

Observations made on IC 1396 and NGC 7000 show an Hα/[N II] profile-width ratio close to the theoretical ratio, $\sqrt{14}$. This ratio does not appear strongly affected by turbulence in NGC 7000, and a temperature evaluation yields approximately 6000 °K (Courtès 1960, p. 179; Cruvellier 1967).

b. General survey of the kinematics of galactic H II *regions*

The radial velocity of Hα emission has been measured at more than 4000 points in the Milky Way. We have published a catalogue of radial velocities of 160 H II regions (Courtès *et al.* 1966), and presented this material at the Toronto Symposium on Radial Velocities (Courtès *et al.* 1967*b*).

The main purpose of this survey was to relate the exciting stars, which are obviously connected with the H II regions in question, to the spiral structure of interstellar hydrogen as traced by radio surveys of the 21-cm line. We assume that, when one observes the same radial velocity for Hα and for the 21-cm line, and sometimes also for the interstellar absorption lines of Ca II or Na I, the spiral arm can be reliably defined and the exciting stars can be located in it with confidence. This study is particularly accurate in the range of galactic longitudes where the differential-rotation effect is strong (Perseus-Cassiopeia). It can strengthen the relationship between the distances computed from kinematical models of the Galaxy and those determined by methods of stellar spectrophotometry.

The results of this survey indicate good general agreement between the radial velocities

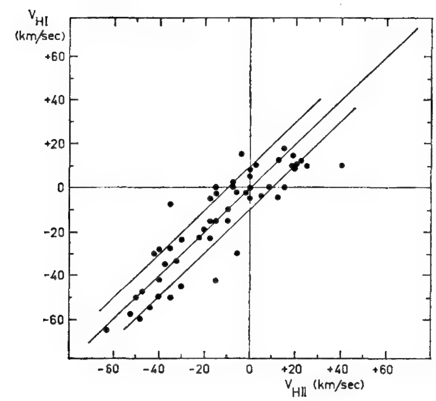

FIG. 1. Comparison of radial velocities obtained by radio methods (21-cm line) with those determined by optical methods (Hα) (Cruvellier 1967). Since the observational errors in this comparison are estimated to be of the order of 10 km/sec, the velocities determined by both methods are in good agreement.

of Hα, the 21-cm line, and the Ca II absorption lines. The best correlations are found in the Perseus Arm. Figures 1, 2 and 4 contain comparisons of the velocities of neutral and of ionized hydrogen.

The Sagittarius Arm shows a velocity excess of the order of +15 km/sec with respect to circular motion (Figure 3). A similar excess has been found by Burton (1966) from a 21-cm survey of the Sagittarius Arm (see also Shane, Paper 29 in this volume). In the region of the anti-centre, the gas behaves as expected: its average velocity is zero (Figure 4).

Georgelin and Monnet have reobserved a region close to the galactic centre, between $\alpha = 17^h\ 44^m\!.5$ and $17^h\ 46^m$, $\delta = -30°\ 50'$ and $-31°\ 10'$, using the 1-metre telescope of the Catania Observatory at the kind invitation of Professor Fracastoro. They again have measured velocities of -210 km/sec, in confirmation of earlier results (Courtès and Cruvellier 1960).

Table 1 (Cruvellier 1967) compares radial velocities measured by us in the Balmer-α line with those determined by Mezger and Höglund (1967) from the hydrogen 109α line. The agreement is generally excellent.

Table 1

Radial velocities of H II regions from optical and radio observations

Name of H II region	Heliocentric radial velocities (km/sec) Optical (Hα)	Radio (109α)
IC 1805	− 48·0	− 47·7
Orion	+ 18·0	+ 16·1
IC 434	+ 37·0	+ 21·9
M 8	− 6·5	− 8·1
M 16	+ 15·5	+ 13·5
M 17	+ 9·3	+ 3·8

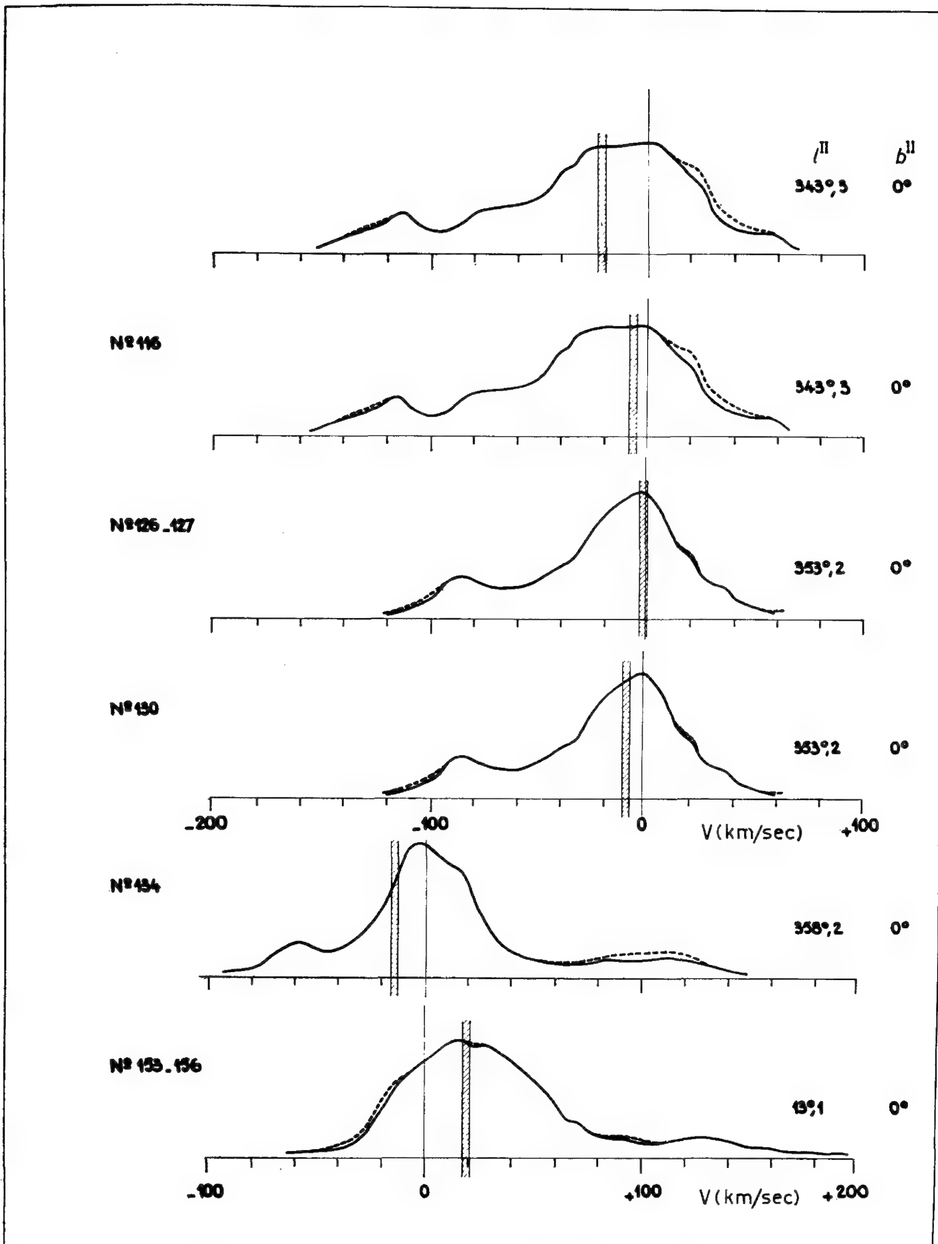

FIG. 2. Comparison of 21-cm profiles (Kerr *et al.* 1959) with radial velocities of H II regions determined by optical interferometry (Cruvellier 1967). The hatched interval indicates the uncertainty of the optical velocities.

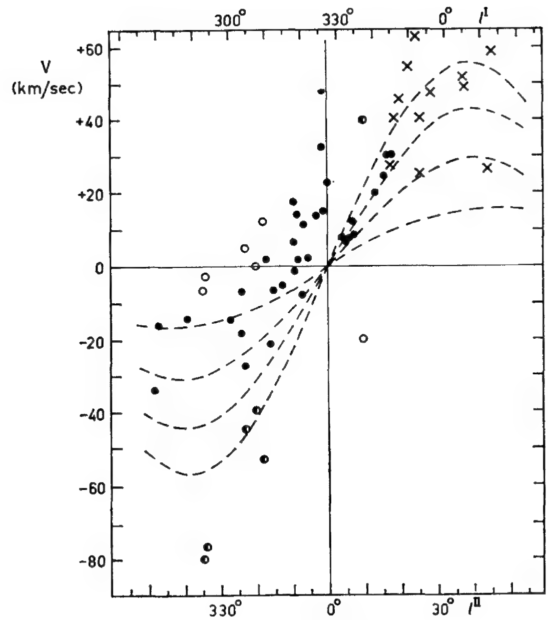

FIG. 3. Radial velocities observed in the general direction of the galactic centre. Crosses: distant OB stars (Münch and Münch 1960); open circles: nearby interstellar Ca II absorption in distant OB stars (Thackeray 1964); half-filled circles: distant interstellar Ca II absorption in distant OB stars (Thackeray 1964); filled circles: H II regions (Cruvellier 1967). The dashed curves indicate differential galactic rotation for objects with circular velocity at distances of 1, 2, 3 and 4 kpc from the Sun.

2. EXTRAGALACTIC STUDIES

Photographs of galaxies such as those in the Hubble Atlas are overexposed in the central condensations, and the use of the normal monochromatic filters is insufficient to bring out the Hα or [O II] emission of H II regions in these central parts. For similar reasons, the bright blue stars are also difficult to detect there, so that no Population-I objects are known. Many galaxies, however, show bright H II regions in their central parts as soon as one uses selective interference filters (Courtès *et al.* 1967*a*). M 33, with its nuclear extensions of Hα (Courtès and Cruvellier 1965) is certainly the best example of this kind of observation, but the detection of Population-I objects near the nuclei of galaxies is a general phenomenon. The main results of our photographic and spectrographic work on galaxies have been discussed elsewhere (Courtès and Cruvellier 1965, Courtès *et al.* 1967*a*).

Another important observation is the systematic stratification in spiral arms, with a very narrow spiral distribution of young blue clusters and H II regions on the outside, and dark clouds most frequently on the inside of the spiral arms. We are now making new, quantitative studies of this stratification effect, using the multiple-passband filter (filtre BPM). The first results of this work were communicated at the Erevan Symposium (Courtès *et al.* 1967*a*).

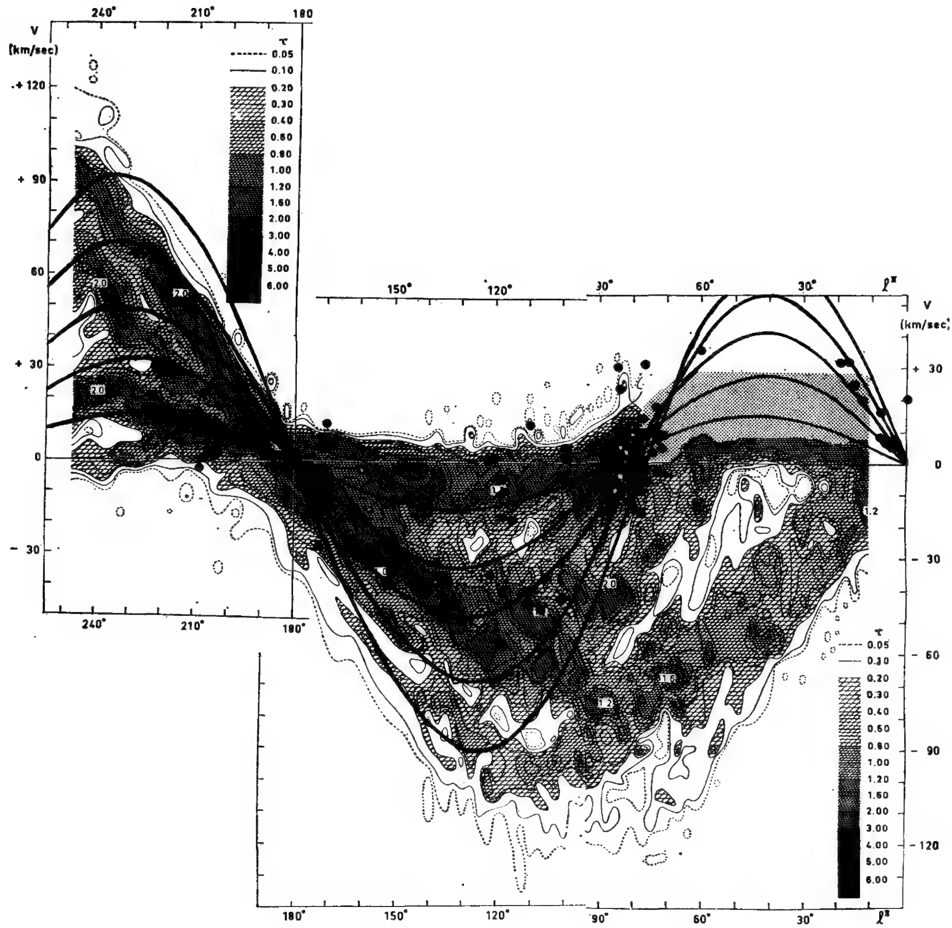

FIG. 4. Velocities of galactic H II regions (Courtès *et al.* 1966) superposed on a plot of optical depth τ in the 21-cm line, as a function of galactic longitude l^{II} and velocity V with respect to the local standard of rest. The 21-cm data have been reproduced from P. O. Lindblad (1966).

We have extended our radial-velocity observations of H α to some extragalactic nebulae. The Proceedings of the Erevan Symposium contain a determination of the rotation curve of M 33 by means of the interference method (Courtès and Georgelin 1967); for more recent results (Carranza *et al.* 1967) see Figure 5.

3. CONCLUDING REMARKS

The results of our H α radial-velocity measures of H II regions in the Galaxy and in the nearest external galaxies can, in combination with radio studies, give a good picture of galactic structure. Measurements of Population-I stars and of interstellar absorption lines are relatively easy to obtain.

It is more difficult to get a good idea of the behaviour of the great star clouds in the Milky Way and in other galaxies. We are trying to use a scanning interferometer on the H and K lines, in the hope of obtaining the radial velocities of such star clouds. The Andromeda Nebula will be the first object to be observed with this new method; sensitivity tests have shown that a resolution of 0·5 kpc should be obtainable in this system.

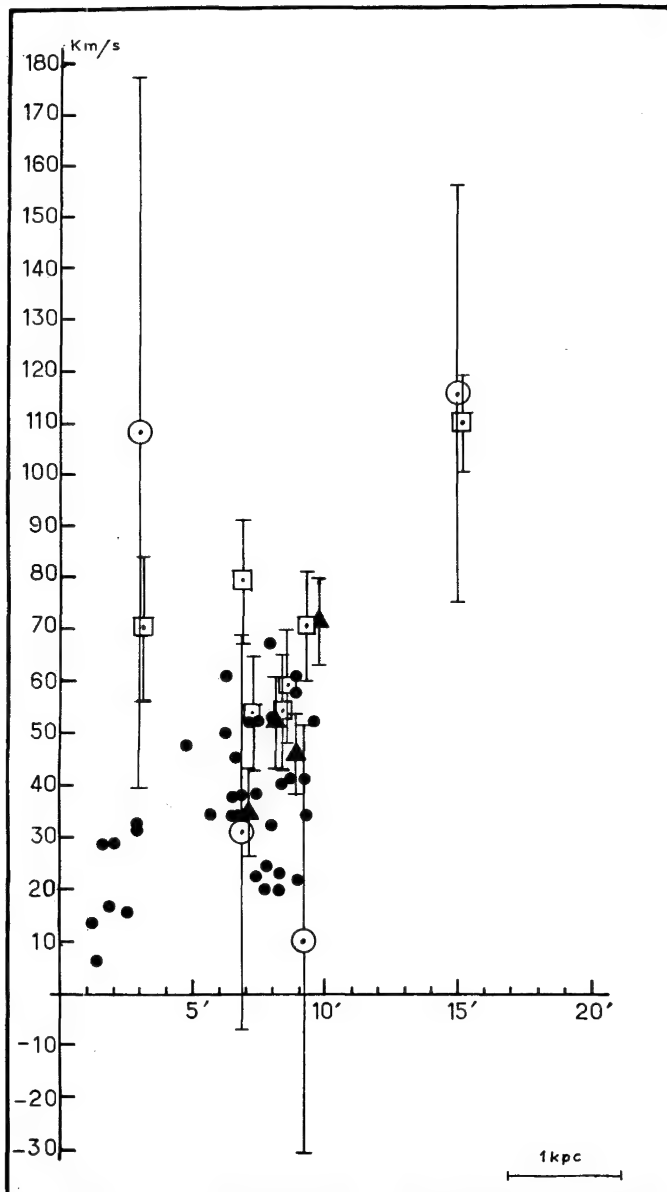

FIG. 5. Rotation curve of M 33, along the major axis, from velocities of H II regions. Spectroscopic results (circles: Mayall and Aller 1942, squares: Brandt 1965) are given with error bars; interference results (triangles: Courtès and Georgelin 1967, dots: Carranza *et al.* 1967) have errors of the order of the size of the symbols.

REFERENCES

Brandt, J. C. 1965, *Mon. Not. R. astr. Soc.*, **129**, 309.
Burton, W. B. 1966, *Bull. astr. Inst. Netherl.*, **18**, 247.
Carranza, G., Courtès, G., Georgelin, Y., Monnet, G. 1967, *C. r. hebd. Sèanc. Acad. Sci.*, Paris, **264**, Sèr. B, 191.
Courtès, G. 1960, *Ann. Astrophys*, **23**, 115.
Courtès, G., Cruvellier, P. 1960, *C. r. hebd. Séanc. Acad. Sci.*, Paris, **251**, 2470; also in 1960, *Publ. Obs. Hte-Provence*, **5**, no. 26.
Courtès, G., Cruvellier, P. 1965, *Ann. Astrophys.*, **28**, 683.
Courtès, G., Georgelin, Y. 1967, IAU Symposium, no. 29 (in press).
Courtès, G., Cruvellier, P., Georgelin, Y. 1966, *J. Observateurs*, Marseille, **49**, 329.
Courtès, G., Demoulin, M. H., Georgelin, Y., Viton, M. 1967*a*, IAU Symposium, no. 29 (in press).
Courtès, G., Cruvellier, P., Georgelin, Y. 1967*b*, IAU Symposium, no. 30, *Determination of Radial Velocities and their Applications*, Eds. A. H. Batten and J. F. Heard, p. 123, Academic Press, London.
Cruvellier, P. 1967, *Ann. Astrophys.*, **30** (in press).
Kerr, F. J., Hindman, J. V., Gum, C. S. 1959, *Austr. J. Phys.*, **12**, 270.
Lindblad, P. O. 1966, *Bull. astr. Inst. Netherl. Suppl. Ser.*, **1**, 77.
Mayall, N. U., Aller, L. H. 1942, *Astrophys. J.*, **95**, 5.
Mezger, P. G., Höglund, B. 1967, *Astrophys. J.*, **147**, 490.
Münch, G., Münch, L. 1960, *Astrophys. J.*, **131**, 253.
Thackeray, A. D. 1964, IAU Symposium, no. 20, *The Galaxy and the Magellanic Clouds*, Eds. F. J. Kerr and A. W. Rodgers, p. 155, Austr. Acad. Sci., Canberra.

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38. A SURVEY OF RECOMBINATION-LINE RADIATION FROM GALACTIC H II REGIONS

(Invited Paper)

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ABSTRACT

This paper summarizes the results of observations of the hydrogen 109 α line at 5009 MHz in galactic H II regions.

The possibility of observing recombination lines of hydrogen and helium atoms in the radio spectrum has been first suggested by Kardašev (1959). Six years later, Höglund and Mezger (1965) detected the 109 α line of hydrogen. Their paper includes a short account of the earlier observations of recombination lines made mainly in Russia.

After the detection of the 109 α line we have carried out a survey of 20 galactic sources, both in this line (Mezger and Höglund 1967) and in the continuum (Mezger and Henderson 1967). The following is a summary of the results presented in these two papers.

The *observable quantities* are:

(1) the excess line temperature, T_L;

(2) the half-power width of the line, $\Delta\nu_L$;

(3) the frequency shift of the line centre with respect to the rest frequency;

(4) the brightness temperature, T_C, of the continuum on which the recombination-line profile is superimposed.

From these observable quantities we can derive the physical conditions prevailing in galactic H II regions, and the distribution of these H II regions in the galactic plane.

The ratio of excess line and continuum temperatures depends on the electron temperature: $\Delta\nu_L T_L/T_C \sim T_e^{-1.15}$. This allows us to compute the *electron temperatures*, T_e; we found an average value of 5800 °K for the spiral-arm H II regions investigated.

Even in Orion A the observed line profiles can very well be approximated by Gaussian functions. The absence of any noticeable Stark broadening, originally a puzzle, has in the meantime been explained in an improved theory by Griem (1967). Since only Doppler broadening is effective and the electron temperature is known, we can determine the *r.m.s. velocity of the turbulence* within the emission regions. Nearly all H II regions investigated have turbulence velocities considerably higher than the velocity of sound.

*The National Radio Astronomy Observatory is operated by Associated Universities, Inc., under contract with the National Science Foundation.

Goldberg (1966) has shown that, under appropriate physical conditions, one should expect enhanced line radiation as a result of stimulated emission. Our observations yield no evidence for such a maser effect, with the exception of the thermal component in W 49 (Mezger *et al.* 1967), where condensations of extremely high electron density and emission measure are embedded in an H II region of lower electron density and larger apparent diameter.

The investigation of the recombination-line spectrum offers a unique possibility to *discriminate between thermal and non-thermal radio sources*. In non-thermal sources the electron temperatures and/or the r.m.s. velocities of internal turbulence are much higher than in normal H II regions, so that the recombination lines are completely washed out (Höglund and Mezger 1965). We have successfully applied this method to several radio sources in W 49, in W 51, and in the Sagittarius region (Mezger and Höglund 1967; see also Kerr, Paper 42, and Lequeux, Paper 68, in this volume).

Using a model of galactic rotation, we have determined kinematic *distances* from the observed radial velocities of H II regions. We resolved the distance ambiguity by combining the recombination-line spectra with 21-cm absorption spectra of the sources investigated. The most distant source in our survey, W 49, yields a kinematic distance of 14·1 kpc. This shows that a more complete survey of the recombination-line radiation of galactic H II regions should be able to furnish a good picture of the distribution of these H II regions in our Galaxy. We estimate that, with an improved line radiometer, we should be able to detect minimum line temperatures of 0·1 °K. With the 140-foot (43-m) telescope operating at 5 GHz (wavelength 6 cm), this would correspond to H II regions (of small apparent diameter) with a minimum flux density of 4 flux units in the continuum. A recent continuum survey at 2·7 GHz (Altenhoff and Mezger 1967) has shown that there are about 150 sources between $l^{\mathrm{II}} = 0°$ and 60° with flux densities exceeding 4 flux units at this frequency.

REFERENCES

Altenhoff, W., Mezger, P. G. 1967, in preparation.
Goldberg, L. 1966, *Astrophys. J.*, **144**, 1225.
Griem, H. R. 1967, *Astrophys. J.*, **148**, 547.
Höglund, B., Mezger, P. G. 1965, *Science*, **150**, 339.
Kardašev, N. S. 1959, *Astr. Zu.*, **36**, 838 (translation in 1960, *Soviet Astr.*, **3**, 813).
Mezger, P. G., Henderson, A. P. 1967, *Astrophys. J.*, **147**, 471.
Mezger, P. G., Hoglund, B. 1967, *Astrophys. J.*, **147**, 490.
Mezger, P. G., Schraml, J., Terzian, Y. 1967, *Astrophys. J.*, in press.

Discussion

R. L. Minkowski: There is just one remark I should like to make on this question of thermal and non-thermal sources. If you do not see hydrogen emission, the source is likely to be non-thermal. If you see hydrogen emission, this does not prove that the source is thermal. Some supernova remnants, like the Crab Nebula or the Cygnus Loop, have quite strong optical emission. You are very likely to find hydrogen emission lines in them, but these sources still are non-thermal.

P. G. Mezger: The problem is that the ratio of the lines to the continuum depends

directly on the electron temperature, and I think the electron temperatures in supernova remnants are much higher than in H II regions.

Minkowski: The electron temperature in the Crab Nebula is 17 000 °K, which is not very much higher than in H II regions. In such things as the Cygnus Loop it seems to be considerably higher, but the main point is that the presence of an emission line does not prove that the source is thermal.

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39. OBSERVATIONS OF THE 158α RECOMBINATION LINE

NANNIELOU H. DIETER

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At Hat Creek I have observed the 158α line at 1651 MHz in seventeen H II regions, some in common with Mezger and Höglund (1967) and some additional ones. The Cygnus-X region in particular has, in this preliminary survey, yielded four sources of the 158α line. A further survey of about forty H II regions will be undertaken soon.

The observations were made with the 100-channel receiver, with a velocity resolution of 2 km/sec. The velocities derived for the sources also observed by Mezger and Höglund (1967) at 5009 MHz all agree with their values within the estimated errors. The line widths all are as would be predicted on the basis of Doppler broadening alone. The electron temperatures derived are about 5300 °K for all the observed sources, slightly lower than the average of 5800 °K found at 5 GHz by Mezger and Höglund (cf. Mezger, Paper 38 in this volume). The individual values are certainly not all in perfect agreement, however. These disagreements may well be resolved upon close examination of the details of observation. The errors in these measurements, amounting to about 1000 °K in the electron temperature, are largely due to uncertainties in the measurement of the continuum. Some differences may still remain after refinement of the data, and these may perhaps be attributable to maser action. We do not yet know for certain.

I have plotted, as suggested by Mezger and Höglund, the emission measures against the observed electron temperatures, to look for a possible correlation to be expected from the maser mechanism. No such correlation appears.

For all the H II regions in which we have found OH emission, I have measured velocities in the 158α line. These indicate a close correspondence with the OH velocities, and thus strengthen the view that the OH emission regions are physically associated with the H II regions.

REFERENCE

Mezger, P. G., Höglund, B.   1967, *Astrophys. J.*, **147**, 490.

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40. CONTINUUM OBSERVATIONS OF THE MILKY WAY

F. J. KERR*

(*CSIRO Radiophysics Laboratory, Sydney, Australia*)

This is a brief report on an extensive program which will eventually cover the Milky Way strip accessible from Parkes at wavelengths of 20 and 11 cm. Various people have been involved, in particular E. R. Hill and M. Beard.

The first large survey was that by Hill at 20 cm of the region $l^{II} = 280°$ to $355°$, $b^{II} = -6°$ to $+6°$, in which a major objective was the development of the necessary data-processing techniques. Hill's map contains many sources, of which two fairly strong ones are non-thermal. The Norma spiral arm shows clearly around 327°, where there is a step in the level, a cluster of sources, and the start of a new extended component. At 11 cm, Beard and others have covered various sections. The results for longitudes 330° to 334° have been published (Beard 1966), and those for 28° to 38° and 345° to 5° are being processed. For each region, in addition to a source list, maps will be published for 20 and 11 cm, and also for the ratio of the intensities at the two wavelengths, with the 11-cm map convolved to the 20-cm beamwidth.

An example of more detailed work on a small region is the study of the Carina nebula by Beard and Kerr (1966). Internal structure was found, which was related to the optical regions of high excitation. There was no radio feature associated with the well-known stellar object η Car.

REFERENCES

Beard, M. 1966, *Austr. J. Phys.*, **19**, 141-146.
Beard, M., Kerr, F. J. 1966, *Austr. J. Phys.*, **19**, 875-881.

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41. A RADIO METHOD OF SEARCHING FOR FINE STRUCTURE IN H II REGIONS

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Fine structure with a scale size of about 10^{-3} pc in the galactic ionized hydrogen may scatter the low-frequency radio emission of extragalactic sources with intrinsically small angular diameters, thus making them apparently large. For example, application of the Chandrasekhar scattering formula to a path length of 100 pc through an H II region with an average electron density of 0·1 cm^{-3}, and structure of scale size 10^{-3} pc filling 1% of the volume, results in a scattering to half-brightness points of 8″ (arc) at 38 MHz. Radio sources with apparent angular sizes of this amount should be partially resolved by an interferometer with an effective baseline of about 10 000 wavelengths.

An interferometer operating at 38 MHz with a north-south spacing of 16 200 wavelengths between Jodrell Bank and the Royal Radar Establishment, Great Malvern, has been used to measure the angular sizes of a number of quasars and radio-galaxies. The eighteen sources which gave detectable fringe patterns in this experiment, including four sources with $|b| < 10°$, show that in these directions the angular diameters of the scattered distributions are less than 5″ (arc). The corresponding limits which can be placed on the average electron density and/or on the scale size of irregularities depend upon the path length through the scattering region. For the sources of high latitude, where the total path length is unlikely to exceed 100 pc, the average electron density is less than 0·1 electrons cm^{-3} and/or the scale size is greater than 10^{-3} pc; at low galactic latitudes, where the path length may be an order of magnitude greater, the above limits are conservative. The estimate assumes that the volume filling factor is less than 5%.

Further measurements with long-baseline interferometers at 38 MHz (or preferably lower frequencies) may be successful in detecting interstellar scattering in some directions near the galactic plane, or, at least, in placing more stringent limits on the interstellar scattering function.

*On leave from the Division of Radiophysics, CSIRO, Sydney, Australia.

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Chapter II D

The Central Region of the Galaxy

CHAIRMAN: J. R. Shakeshaft

(*Mullard Radio Astronomy Observatory, University of Cambridge, Cambridge, England*)

'How long will it be before we have a geometrical determination of the distance to the galactic centre, from proper motions?'
'Do you mean: how many centuries?'

D. Lynden-Bell and J. H. Oort,
in the Discussion of Paper 25

42. INTERSTELLAR GAS IN THE CENTRAL REGION OF THE GALAXY

(Introductory Report)

F. J. KERR*

(*CSIRO Radiophysics Laboratory, Sydney, Australia*)

ABSTRACT

A review is given of information on the galactic-centre region obtained from recent observations of the 21-cm line from neutral hydrogen, the 18-cm group of OH lines, a hydrogen recombination line at 6 cm wavelength, and the continuum emission from ionized hydrogen.

Both inward and outward motions are important in this region, in addition to rotation. Several types of observation indicate the presence of material in features inclined to the galactic plane. The relationship between the H and OH concentrations is not yet clear, but a rough picture of the central region can be proposed.

1. INTRODUCTION

This review covers the observational material on the central region, with particular reference to the most important results from recent work.

Optical observations can tell us little about the central part of the Galaxy. In the radio spectrum, we have information from the 21-cm line of neutral hydrogen, the 18-cm group of OH lines, a hydrogen recombination line at 6 cm, and also the continuum emission from ionized hydrogen. Details of the continuum sources are discussed by Lequeux (Paper 68) in a later section of this Symposium, but some aspects of the continuum data will be referred to here.

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It is worth saying at the outset that the gas represents a *very* small percentage of the total mass in the central region. The star density increases greatly in going from the Sun to the galactic centre, but the gas density does not—in fact, it decreases. The reasons for studying this small fraction of the central mass are that it is after all the only component that we can observe, and also it shows some very interesting phenomena.

2. NEUTRAL HYDROGEN

The first major survey of 21-cm emission and absorption in the central region was carried out by the Dutch group (Rougoor and Oort 1959), who showed that a large fraction of the hydrogen appears to be moving away from the centre, having at the same time a rotational component of motion. At the very centre, Rougoor and Oort (1960) proposed a rapidly-rotating disk, extending to about 4° in longitude or 700 pc in radius from the centre, and containing about $3 \times 10^6 M_\odot$ of neutral hydrogen. In the outward-moving material the most prominent feature is the 3-kpc arm, which has an outward motion of 53 km/sec at $l^{\text{II}} = 0°$. Rougoor's estimate for the hydrogen mass in this arm is $3 \times 10^7 M_\odot$.

The model proposed by Rougoor (1964) has, outside the nuclear disk, two principal spiral arms in the central few kiloparsecs. These main features are in a very thin layer, closely concentrated to the galactic plane. More recent observations (principally at Parkes) have added greatly to the available information on hydrogen in the region, revealing considerable fine structure and some rather new features.

Very strong absorption effects are observed in the spectrum of the continuum source at the centre, Sagittarius A (Figure 1). Absorption is found over a wide range of negative and positive radial velocities, demonstrating that there is a substantial amount of material

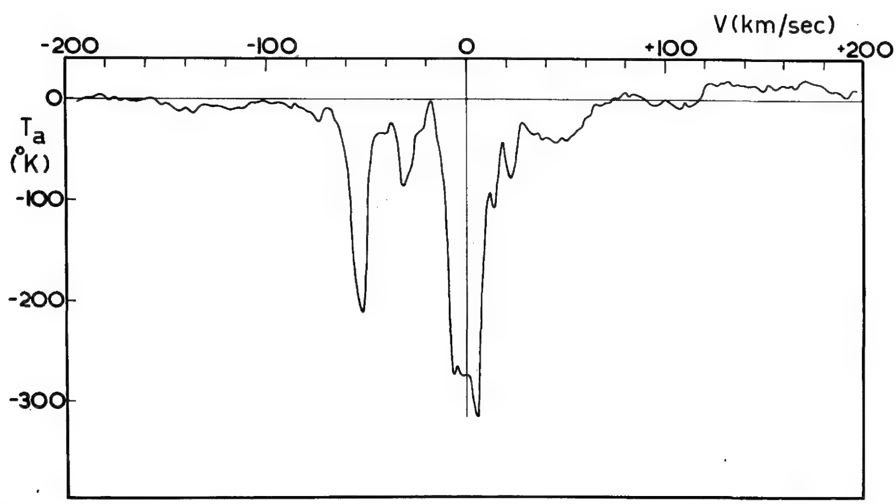

FIG. 1. Hydrogen absorption profile at the position of Sagittarius A, observed with the 210-foot (64-m) Parkes telescope and a frequency-switched receiver of 10 kHz = 2·1 km/sec channel bandwidth. The ordinate is the observed antenna temperature (Kerr and Vallak 1967).

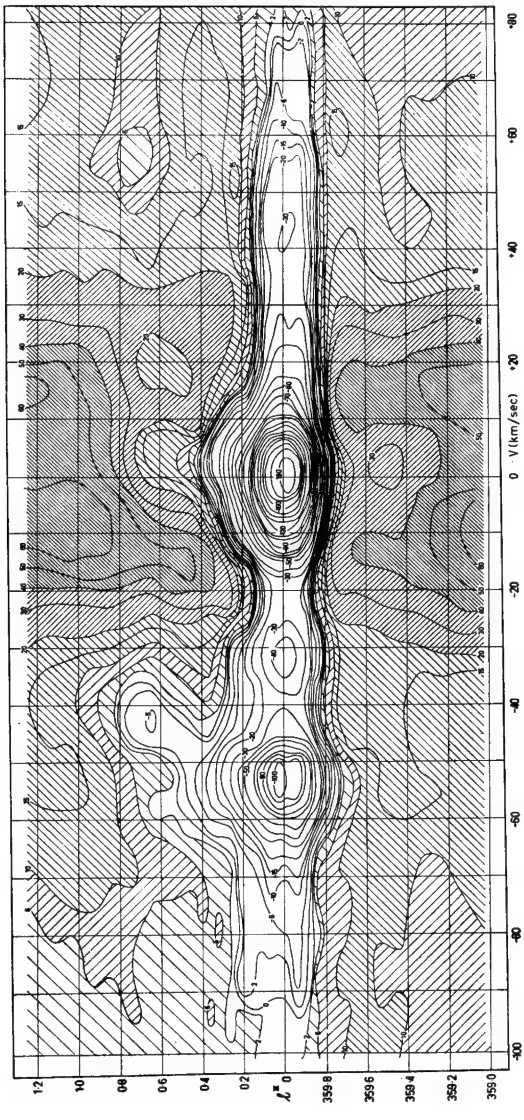

FIG. 2. Contour diagram of 21-cm line intensity in the longitude-velocity plane for the galactic equator from l^{II} = 359°·0 to 1°·2. The scale unit is 1·4 °K of antenna temperature; the receiver bandwidth 36 kHz = 7·6 km/sec (Kerr and Vallak 1967).

with an inward component of motion, towards the centre, in addition to the outward-moving gas. The deepest component in the spectrum is mainly produced by hydrogen in the spiral arms outside the nuclear region. This dip is accurately symmetrical about zero velocity, indicating that this hydrogen has no mean radial motion. The 3-kpc arm, and another arm at −30 km/sec, are clearly evident. There are also components in the vicinity of −130 and +40 km/sec, the velocities of the main OH components, but these are much less prominent in hydrogen than they are in OH.

More detail of the central absorption is shown in the equator diagram of Figure 2

(Kerr and Vallak 1967). The broad component near zero velocity displays a gradient towards more positive velocity with increasing longitude, which implies that this absorption is occurring in the rotating nuclear disk. This effect is more clearly visible on the northern (positive-longitude) side of the centre.

We now turn our attention to a larger region. Figure 3 shows the broad features in the equator in the longitude range 340° to 20°. This diagram is drawn from profiles observed at points 1° apart, with the 0° profile omitted because the central absorption gives a discontinuity in the general pattern. The low-velocity ridge, due to the nearer hydrogen, stands out in the middle of the diagram; so does the 3-kpc-arm ridge on the negative-velocity side. The higher-velocity material is clearly asymmetrical in its distribution, but it appears mostly in the two quadrants of the diagram that are associated with rotational motions. There is however some high-velocity gas in the 'forbidden' velocity regions, the other two quadrants of the diagram.

Most of the central-region hydrogen is in a thin layer very close to the galactic plane, but there is also some material out of the plane which has very interesting characteristics. Rougoor had already found that at positive longitudes the high-velocity gas has its maximum density out of the plane. The recent surprise is that on the other side of the centre the high-velocity material, which in the plane has vanished by $l^{\mathrm{II}} = 355°$, can be followed to 340° at other latitudes.

The behaviour on the two sides of the centre is illustrated in Figures 4 and 5, which give velocity-latitude diagrams for longitudes 348° and 7°. At 348° the negative-velocity hydrogen (i.e. the gas with velocities consistent with galactic rotation) is well north of the plane, on the average. Its maximum density remains to the north all the way to 342°. At 7°, on the other hand, a major portion of the rotating gas (here at positive velocities) is to the south of the plane. At positive longitudes we also find that the high-velocity hydrogen is more detached from the lower-velocity material than is the case at negative longitudes.

The shape of the high-velocity features can be seen in Figure 6, which presents contours for the integrated brightness over a range of negative velocities for $l^{\mathrm{II}} < 0°$ and positive velocities for $l^{\mathrm{II}} > 0°$. Because of the variation of velocity with longitude, it was not convenient to take a fixed velocity range for the integration. Instead, the outermost 70-km/sec interval on the appropriate side of the profile was used at each longitude, the integration range remaining the same for all latitudes at a given longitude. (Note the expanded latitude scale in Figure 6.)

The high-velocity gas appears to be in a single inclined feature, inclined about 8° to the plane, in the central range of longitude, returning to the plane as we go further out from the centre on each side. On the southern (negative-longitude) side, the high-velocity component seems to join the 3-kpc arm at about 340°, but it probably fades out at $l \approx 10°$ to 12° on the other side. This tilted hydrogen feature suggests a rudimentary bar, extending outwards from the nuclear disk. Its motion could be rotational alone, or rotation plus expansion.

Structures inclined to the galactic plane have been found in two other ways. Firstly, in 20-cm continuum observations (Kerr and Sinclair 1966; see also Paper 69 in this Symposium volume), there are inclined features near the centre with the same sense of tilt as the possible hydrogen bar, but a steeper tilt angle (about 50°). These can be seen in Figure 7. They give the impression of jets, with material streaming out in two nearly opposite directions.

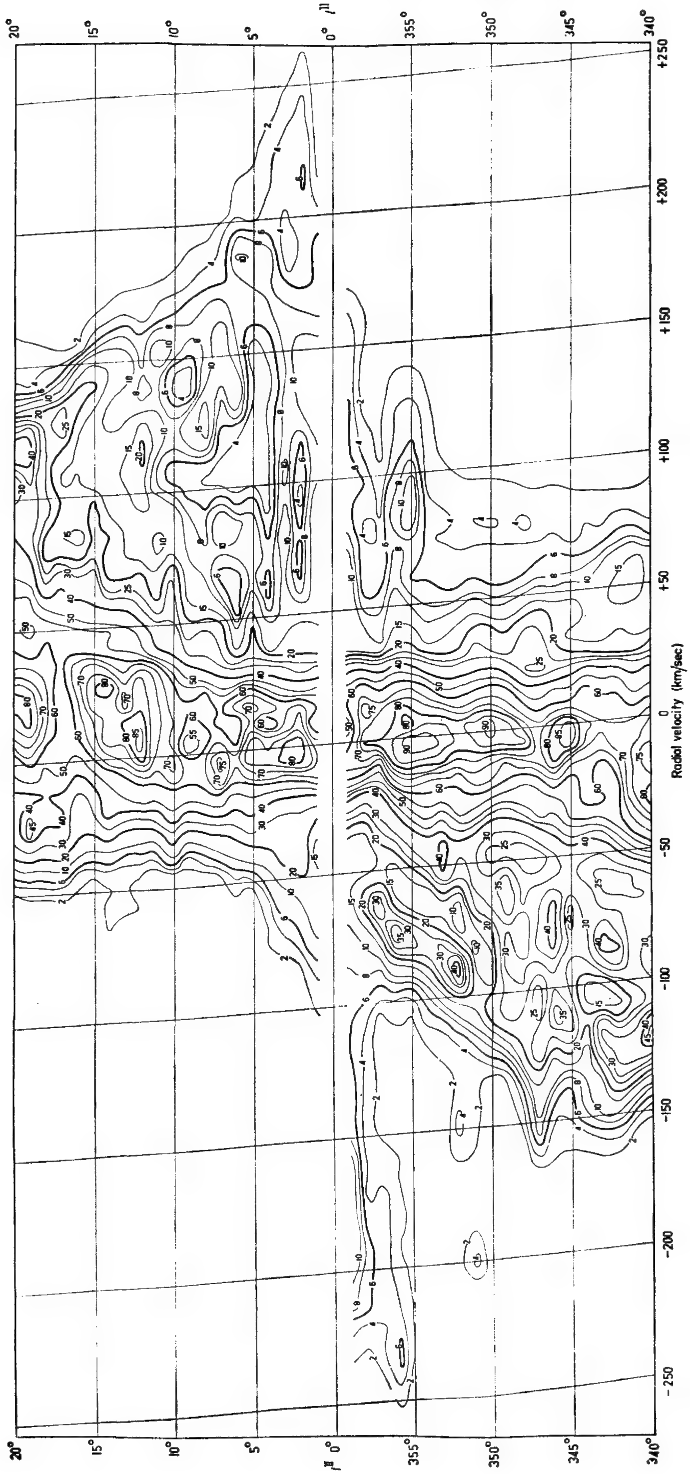

FIG. 3. Contour diagram of 21-cm line intensity in the longitude-velocity plane for the galactic equator from $l^{II} = 340°$ to $20°$, based on profiles at 1° intervals (Kerr, unpublished). The scale unit is 1·4 °K of antenna temperature; the bandwidth 36 kHz = 7·6 km/sec.

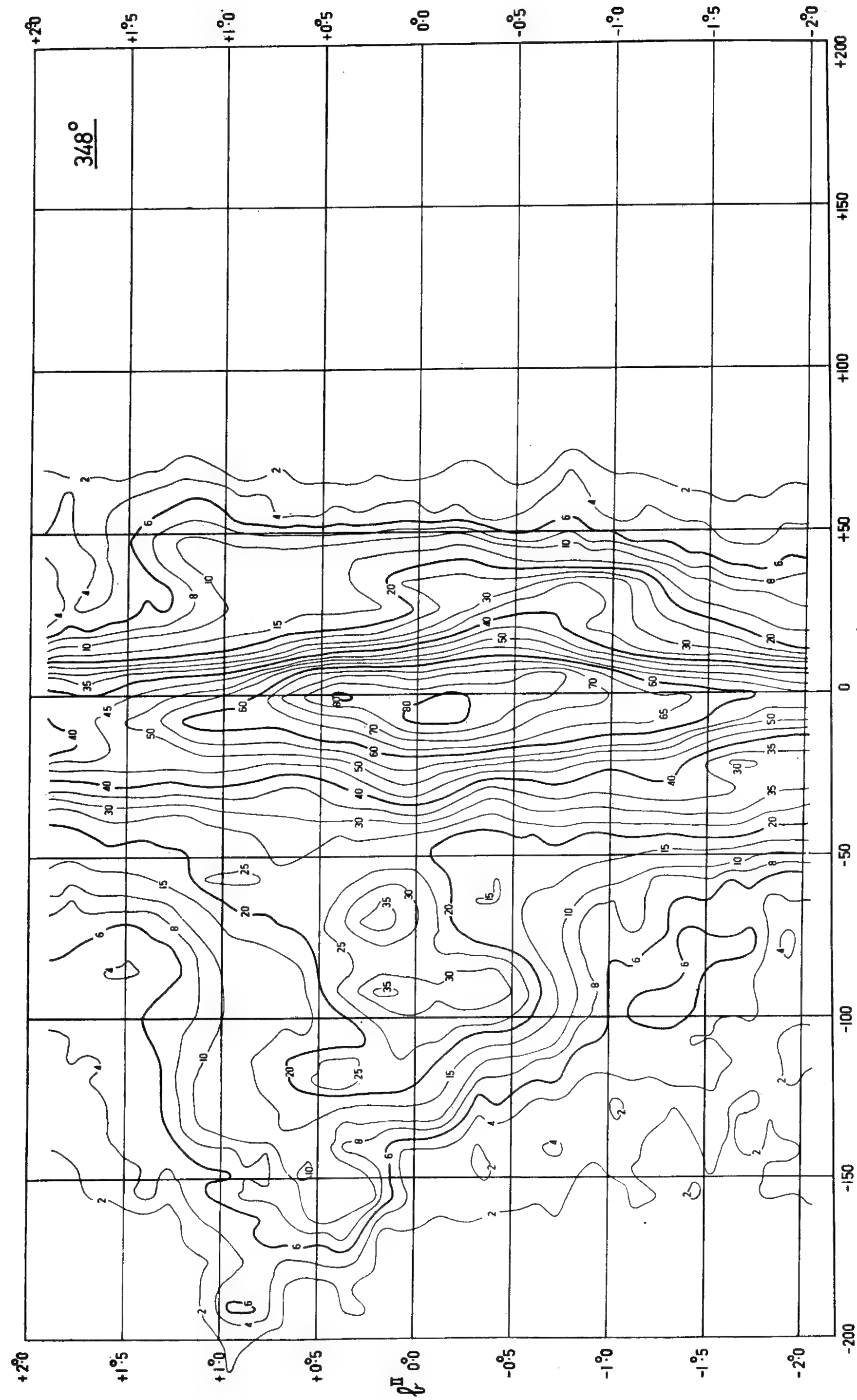

FIG. 4. 21-cm contour diagram in the latitude-velocity plane for $l^{II} = 348°$ (Kerr, unpublished).

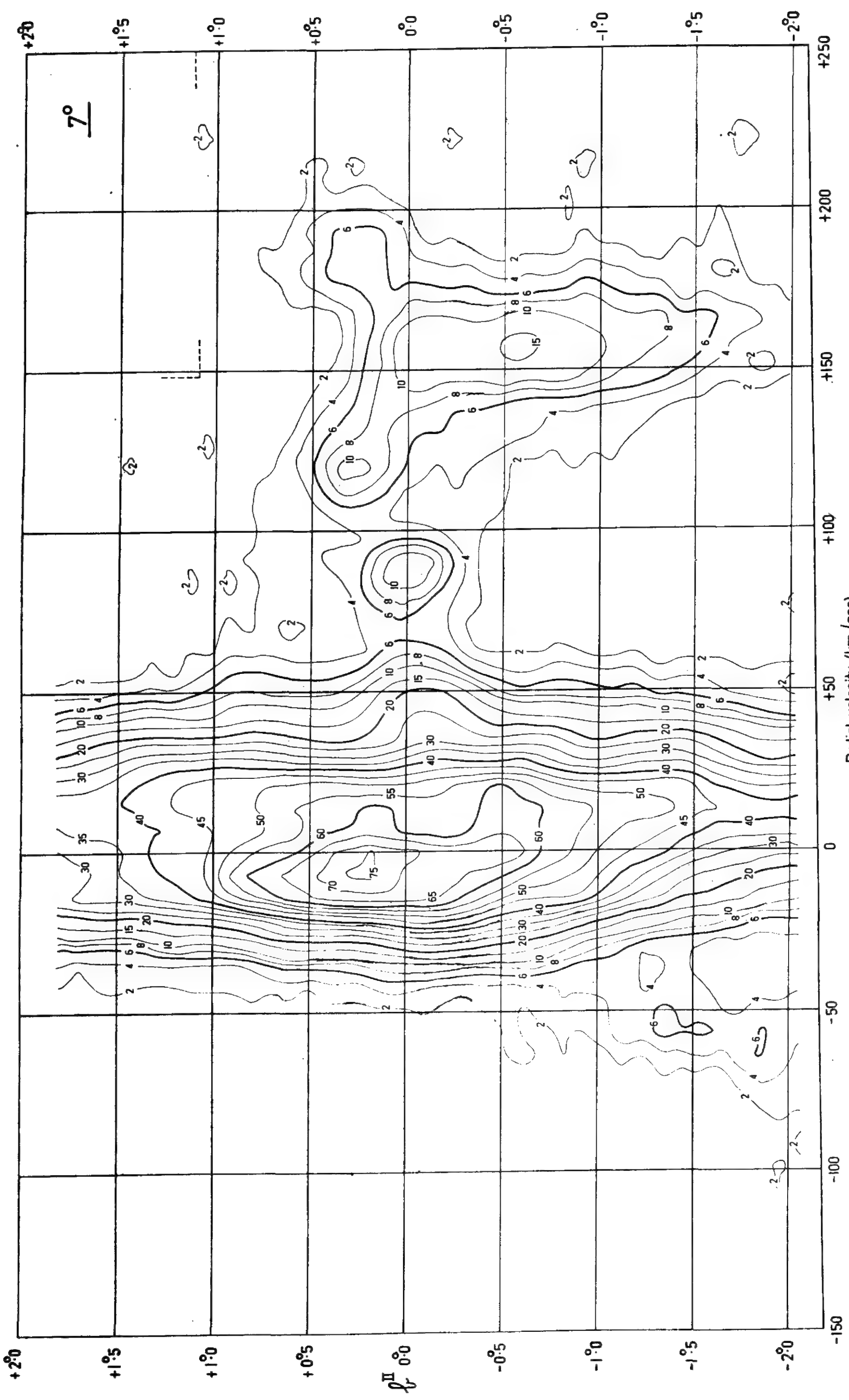

FIG. 5. 21-cm contour diagram in the latitude-velocity plane for $l^{II} = 7°$ (Kerr, unpublished).

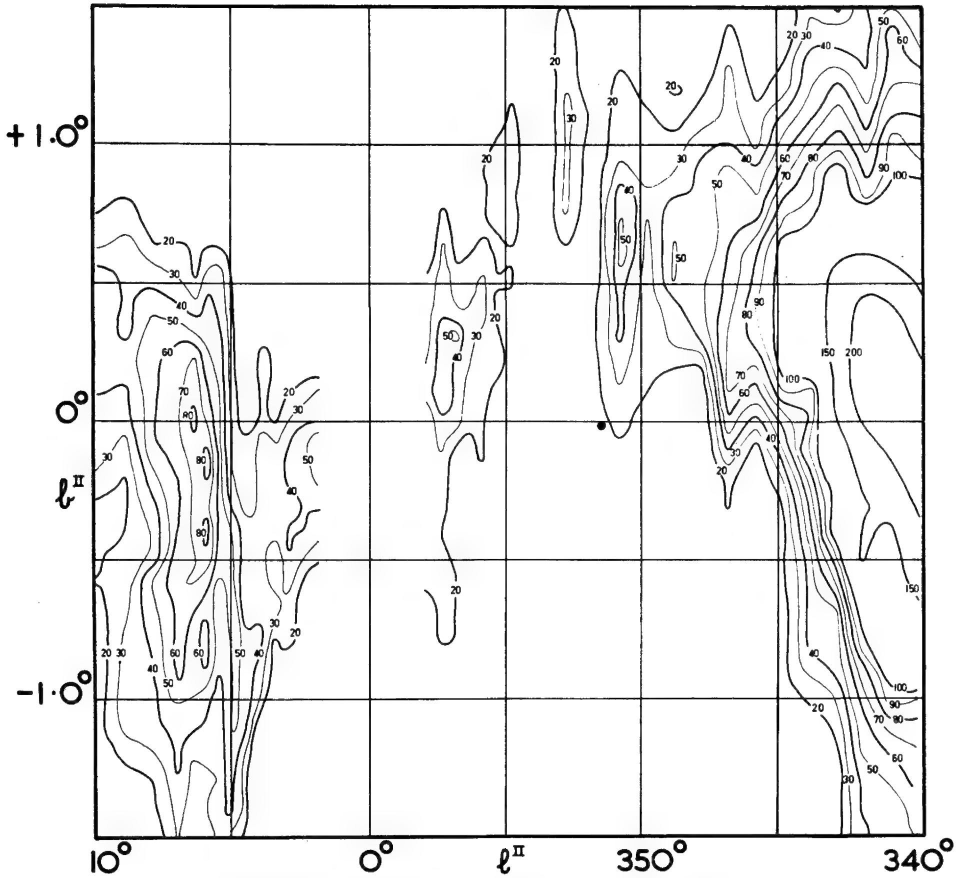

FIG. 6. Integrated brightness of high-velocity hydrogen, see text.

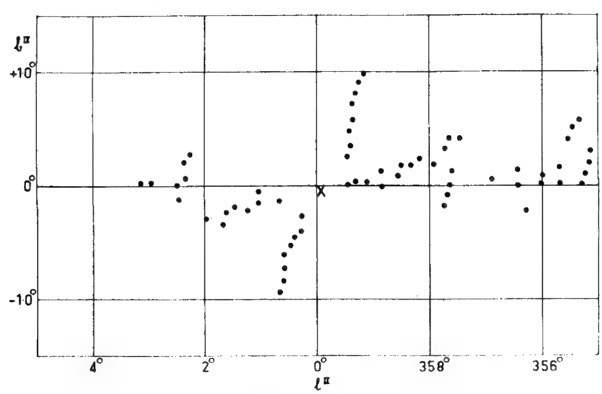

FIG. 7. Location of 20-cm continuum 'ridge lines' in the galactic-centre region (Kerr and Sinclair 1966).

Secondly, observations by Shane (Oort 1967; see also Paper 29 in this volume) have shown that the high-velocity features at forbidden velocities are quite extended in size, and patchy in nature. Detailed observations are not yet complete, but the group of clouds extends to $\pm 4°$ in latitude and covers the range 350° to 10° in longitude. These features also suggest the ejection of material, and it is remarkable that the inclined features of all the three types are found in the same two quadrants in projection on the sky.

The 3-kpc arm is one of the most prominent structures in the central region. It was so called because early Leiden and Sydney observations suggested that it was tangential at $l^{II} = 335°$, leading to a distance from the centre of 3 kpc on the old galactic distance scale. On the new ($R_0 = 10$ kpc) scale, the distance from the centre would be 4 kpc, and hence the name might be changed. However, as first shown by Burke and Tuve (1964), this arm is a complex feature and not a single continuous spiral arm. Much detail and complexity are seen in the newer observations; in particular there are branchings or junction points at $l^{II} = 348°$ and 342°. Because the location and shape of the whole feature must now be considered uncertain, we will retain the traditional name of 3-kpc arm at present.

A possible structure for the neutral hydrogen in the central region is shown in Figure 8. In the centre is the nuclear disk, in which there are two sections, the inner one having mainly rotational motion, the outer one probably some radial motion as well. This structure is not as regular or symmetrical as the name disk suggests, but this name is now established. Next we have the postulated bar, joining the 3-kpc arm at one end and

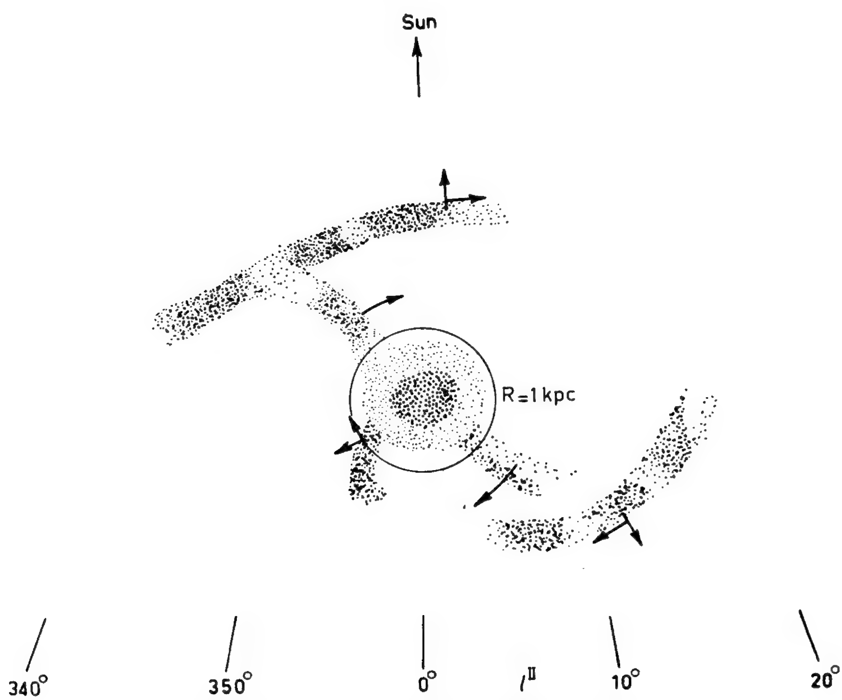

FIG. 8. A possible structure for the galactic-centre region.

fading out at the other end. The 3-kpc arm, a patchy structure, appears on one side, and a less well-marked feature on the other. Shane's tilted feature (and the continuum 'jets') might be at right angles to the bar. As he points out, if the observed velocities represent an outward flow, the features must be in the second and fourth quadrants of Figure 8.

The suggested location of all these features is of course very conjectural. In all cases the gas layer is quite thin, about 100 pc between half-density points, except for a spreading out to 200 pc at the outer edges of the suggested bar. However, the main part of the 3-kpc arm is again thin, about 120 pc.

3. OH MOLECULES

Some aspects of the OH in the central region have been discussed by Robinson in his review (this volume, Paper 7), but not the structural questions.

High optical depths are found for the OH near the centre, and the four lines of the group show anomalous and varying ratios over the region. The OH lines are observable over a much smaller region than the hydrogen, but this has the advantage that individual OH features can be distinguished more clearly. With only minor exceptions, the OH in this region has been seen only in absorption so far. As a consequence, one of the important questions is whether the limits of the region in which OH is found are due to the OH running out, or the continuum background becoming too weak to show absorption.

The OH absorption profile for Sagittarius A is displayed in Figure 9 (Bolton, Gardner, McGee and Robinson 1964). The strong components at -130 and $+40$ km/sec dominate the diagram; the possible hydrogen counterparts of these are quite weak. On the other hand, the components due to nearby OH, and to OH in the 3-kpc arm, are much weaker than the corresponding hydrogen features. An interesting result is that the low-velocity OH component is displaced from zero velocity by a few kilometres per second, unlike the corresponding hydrogen component, which is very symmetrical about zero. (This difference has also been noted by Weaver.) This result presumably refers to gas outside the nuclear region, but, if the OH/H ratio increases progressively from the Sun to the centre, it could be interpreted as implying a systematic variation in the radial component of velocity from one spiral arm to another.

The distribution of the OH in the central region is illustrated in a series of velocity-longitude diagrams to be published by McGee and Robinson. Figure 10 gives the diagram for $b^{\mathrm{II}} = -0°05'$. A number of separate absorption features are identifiable, with different distributions over the sky. The general trend of the pattern is inclined across the diagram in the rotational direction. The slope is comparable with, but slightly less than, that for the hydrogen which has been attributed to the nuclear disk. The -130 km/sec component shows up as a broad, fairly shallow valley, which probably reflects the variation of the continuum background for a broad OH source. The main component, at $+40$ km/sec, however appears as a much steeper hole in the diagram, and it is well separated from a second component at about the same velocity at $l^{\mathrm{II}} \approx 0\overset{\circ}{.}7$. This does not follow the continuum distribution, and the $+40$ OH concentration must therefore be quite small in angular diameter, perhaps a few minutes of arc. The conclusion that the $+40$ object is smaller in size than the -130 one is supported by the relative strengths of the two components in the Parkes and Berkeley observations, with their different beamwidths. Another inference from Figure 10 is that the $+40$ OH concentration does

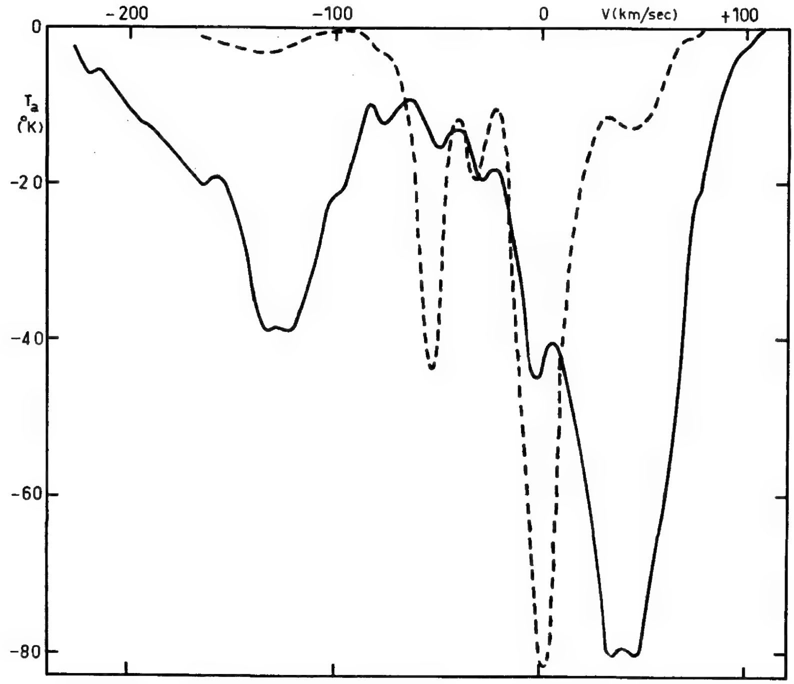

FIG. 9. OH absorption profile for Sgr A (1667 MHz). The 21-cm profile is drawn as a dashed line, on an arbitrary scale (Bolton *et al.* 1964).

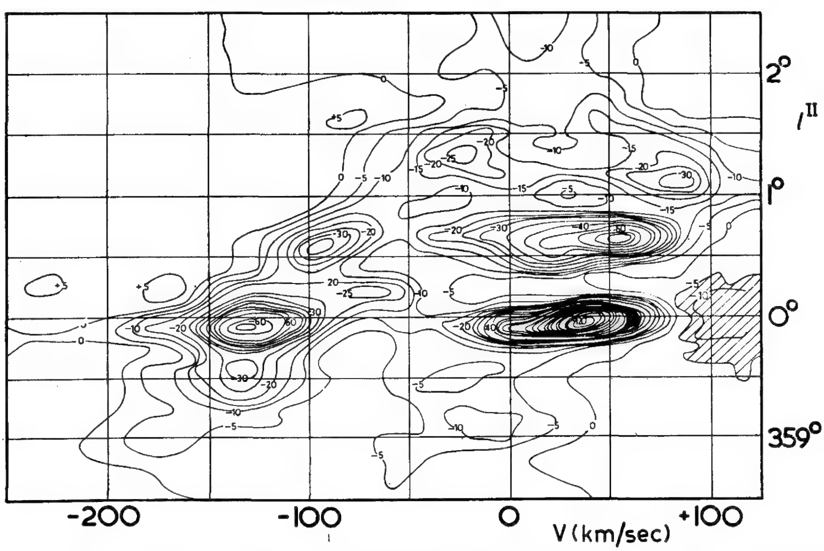

FIG. 10. OH contour diagram (1667 MHz) in the longitude-velocity plane for b^{II} = − 0°05′ (McGee and Robinson, unpublished).

not seem to absorb the extended component of the continuum, which must therefore mainly originate in front of this OH cloud, and in front of Sgr A.

We cannot obtain precise locations for the OH features. All we can do is to order them in distance to some extent. We can guess that the +40 concentration is small and near Sgr A at the galactic centre, while the other objects are further out in the nuclear disk. All the components appear to be in a plane a few minutes of arc below the equator of the coordinate system, and Robinson (cf. Paper 7, Figure 3) considers that they are all more concentrated in latitude than the continuum sources.

4. OTHER CONSTITUENTS

a. Thermal sources

Continuum observations indicate the presence of several thermal sources very close to the galactic centre (cf. Lequeux, Paper 68 in this volume). In addition to these small H II regions, there appears to be a ring of ionized hydrogen at the outer edge of the nuclear region, which may be related to the 3-kpc arm (Westerhout 1958).

b. Excited hydrogen

Mezger and Höglund (1967) have detected excited hydrogen near the centre, in observations of a recombination line near 5000 MHz, corresponding to the transition $n = 110 \rightarrow 109$. The line was found in the continuum sources at $l^{II} = 0^\circ\!.2$ and $0^\circ\!.7$, but not in the strong central source, Sagittarius A. As this line is received only from H II regions, the result supports the view that Sgr A is non-thermal and the other sources are thermal. The observed velocities of the line were +59 and −25 km/sec for the two positions. These values do not directly correspond to peaks in the hydrogen and OH profiles, but the velocities are in the general range where H and OH are found. The electron temperatures deduced from the recombination-line observations are hardly different from those obtained for spiral-arm H II regions.

c. X-ray sources

A number of X-ray sources have been detected in the general direction of the centre, and a possible connection between this cluster of sources and the nuclear region has been discussed by Johnson (1966) and others. However, the spread in latitude amounts to several degrees, implying that the X-ray sources must be in a population which is much more widely dispersed in latitude than Population I, or else they are much closer to us than the centre. Also, there is no coincidence with Sgr A, which is so strong in the radio spectrum.

5. CONCLUSION

The central region is a very interesting one, but there is still much to be learnt about it. Some valuable information should be obtainable from the forthcoming series of lunar occultations of the galactic centre; these should be observed by as many people as possible.

REFERENCES

Bolton, J. G., Gardner, F. F., McGee, R. X., Robinson, B. J. 1964, *Nature*, **204**, 30–31.

Burke, B. F., Tuve, M. A. 1964, IAU Symposium, no. 20, *The Galaxy and the Magellanic Clouds*, Eds. F. J. Kerr and A. W. Rodgers, p. 183–186, Austr. Acad. Sci., Canberra.

Johnson, H. M. 1966, *Astrophys. J.*, **143**, 261–263.
Kerr, F. J., Sinclair, M. W. 1966, *Nature*, **212**, 166–167.
Kerr, F. J., Vallak, R. 1967, *Austr. J. Phys. Astrophys. Suppl.*, *no.* 3, 1–27.
Mezeer, P. G., Höglund, B. 1967, *Astrophys. J.*, **147**, 490–518.
Oort, J. H. 1967, IAU Symposium, no. 29 (in press).
Rougoor, G. W. 1964, *Bull. astr. Inst. Netherl.*, **17**, 381–441.
Rougoor, G. W., Oort, J. H. 1959, IAU Symposium, no. 9, *Paris Symposium on Radio Astronomy*, Ed. R. N. Bracewell, p. 416–422, Stanford Univ. Press, Stanford, California.
Rougoor, G. W., Oort, J. H. 1960, *Proc. nat. Acad. Sci. USA*, **46**, 1–13.
Westerhout, G. 1958, *Bull. astr. Inst. Netherl.*, **14**, 215–260.

NOTE ADDED IN PROOF

Dr G. W. Rougoor, who was one of the main contributors to our knowledge of the central region, attended the Symposium, but died of leukemia on 9 April 1967 at the early age of 36. His untimely death is a great loss to his colleagues in this field.

FJK

I.A.U. Symposium no. 31, 1967

43. DISCUSSION ON INTERSTELLAR GAS IN THE CENTRAL REGION OF THE GALAXY

R. D. Davies: Following the report at the Erevan conference (Oort, J. H. 1966, IAU Symposium no. 29, in press) of weak 21-cm emission at high forbidden velocities near the galactic centre, we have made a preliminary survey of the brighter features mentioned by Oort. Our observations consisted of drift curves across the area with a sensitivity of 0·25 °K in aerial temperature (T_a), and a bandwidth of 50 kHz = 11 km/sec. Around $l^{II} = -1°$, we found hydrogen with velocities of +125 km/sec out to $b^{II} = +1\overset{\circ}{.}5$, with an aerial temperature of 2 °K (brightness temperature 3 °K). At $l^{II} = 4°$, an emission patch of $T_a = 1$ °K was seen at $V = -110$ km/sec and $b^{II} = -2\overset{\circ}{.}5$, separated from the emission in the galactic plane. In both regions the emission was restricted to velocities $|V| < 150$ km/sec.

E. M. Burbidge: In connection with Kerr's suggestion of ejection in two opposite directions at a fairly large inclination to the plane in our Galaxy, I wish to remark that the velocity field in M51, which I only briefly mentioned in Paper 36, also suggests ejection in opposite quadrants at some inclination to the equatorial plane.

The structural appearance of the central regions of many barred spiral galaxies suggests a similar kind of symmetry. One sees two dust lanes in the nuclear region, and, although it is very difficult to determine the spatial orientation of barred spirals, one gets the impression that one lane lies on one side of the plane and the other on the opposite side. Certainly non-axially-symmetric radial flow has been observed in barred spirals, but has not yet been related to the structural features of these dust lanes.

B. J. Robinson: Kerr has stressed the tilt of the continuum features and the high-velocity 21-cm features near the galactic centre. For the hydrogen, the negative velocities (and the 'forbidden' positive velocities) are found at positive latitudes and negative longitudes, and vice-versa. The OH absorption features have a slight tilt in the opposite direction: negative velocities are observed at negative latitudes and longitudes, while the positive-velocity OH tends to lie on or above the plane at positive longitudes. However, the scale of the tilted OH distribution is much smaller than that of the features discussed by Kerr: the OH only extends from $l = 359°$ to $l = 3°$ or $4°$.

Kerr asked in his review whether the OH absorption terminates because we run out of OH or of continuum radiation to be absorbed. The opacity map shown by me earlier (Paper 7, Figure 3) indicates that the OH runs out first; the continuum contours extend well beyond those of the various OH blobs.

G. W. Rougoor: Does the distribution of the OH feature at −130 km/sec really reflect the continuum radiation? From the diagram shown (Figure 10 in Kerr's paper) I have the impression that the small, strong continuum source (Sgr A) is not absorbed at this velocity.

Robinson answers: The OH cloud at −135 km/sec lies south of the galactic plane, and probably does not extend far enough to absorb much of the core source of Sgr A.

H. F. Weaver: The extensive series of measurements carried out at the Hat Creek Radio Observatory, which are now being prepared for publication, make it clear that the interpretation of the OH absorption seen in the direction of the galactic centre will not be easy. A variety of models of the structures from which the lines originate are possible and plausible. Some of these models place the material at very small distances. A detailed discussion of this topic would seem inappropriate here at present, but I believe we should keep it in mind.

The velocity agreement between the H and OH lines at -133 km/sec in the spectrum of Sgr A is excellent. For the feature at $+38$ km/sec, the velocity agreement is poorer than for any other feature shown, and the line shapes and widths are not very similar. The H feature appears to have a much greater angular extent than the OH feature. It is probable that the hydrogen and OH lines on the positive-velocity side do not arise from the same gas structure. Care should be exercised in such identification of the $+38$ km/sec feature.

A collection of OH profiles for $b^{II} = -0\overset{\circ}{.}25$ arranged according to longitude illustrates the velocity field of the OH-rich structures in the region of the galactic centre. The characteristic of the velocity field is that, while a feature varies in strength as a function of longitude, it retains the same velocity. A number of features may be visible at any one longitude.

The Hat Creek contour diagram corresponding to Kerr's Figure 10 covers a larger area of sky and consequently contains more features. The two diagrams are in complete agreement in the overlap area. The increase in resolution afforded by the larger telescope at Parkes is, however, spectacular.

Robinson answers: Parkes observations on a 5′ (arc) grid leave no doubt that the narrow features in the OH profiles at negative velocities are independent, and each persists over only a small range of longitude and latitude. The OH appears to be distributed in isolated blobs, which are just resolved with our 12′ (arc) beam. These blobs are presumably embedded in the negative-velocity hydrogen, and have a comparable spread in velocity and space.

Weaver has questioned whether the *positive*-velocity OH feature really corresponds to the bump on the wing of the H absorption profile of Sgr A. We would not expect a close correspondence in velocity, as the OH appears to be one small blob which absorbs only the core source of Sgr A, not the extended components. The OH is much more restricted spatially than the hydrogen, but must be generally associated with it.

Weaver: I believe that there may be a contradiction in two of Robinson's diagrams that should be cleared up. On the contour diagram shown by Kerr (Paper 42, Figure 10), the various OH-rich features are quite separate. In the discussion, Robinson produced a figure (cf. Paper 7, Figure 3), showing features connected over as much as $1\frac{1}{2}$ degrees of longitude. The Hat Creek observations indicate no such connections, they agree with the Australian countour diagram.

Robinson: The *l*, *b* maps of the separate OH clouds (Paper 7, Figure 3) show contours of *opacity*, whereas the *l*, *V* plot (Paper 42, Figure 10) gives contours of differential antenna temperature of the (absorption) line with respect to the continuum. Thus the continuum sources, which dominate the *l*, *V* plot, are effectively removed from the cloud map.

The opacity at some velocities appears to persist up to a degree in longitude. However

it does seem unlikely that the dumbbell shapes found would be stable with these high velocities, and with higher angular resolution the dumbbells might well break up into two blobs having dimensions of 10 to 20 minutes of arc. We shall soon produce maps of opacity based on the 5′ (arc) grid of the 1965/66 Parkes surveys.

Ju. N. Parijskij: The weak emission at -10 km/sec, observed at Pulkovo in the recombination line 104α at 5·2 cm wavelength (Dravskih, A. F., Dravskih, Z. V., Turevskij, V. M., Solonikov, A. A. 1966, *Astr. Cirk.*, no. 354), may be related to the displacement of the OH absorption near zero radial velocity.

P. G. Mezger: The recombination-line feature mentioned by Parijskij may have been overlooked in our 109 α-line survey (Mezger, P. G., Höglund, B. 1967, *Astrophys. J.*, **147**, 490), since it is very weak and narrow.

In addition I want to mention that both electron temperature and internal turbulence of the two thermal sources* G 0·2 − 0·1 and G 0·7 − 0·1 are very similar to the average values which we obtained for spiral-arm H II regions, although these sources are certainly fairly close to the galactic centre. Consequently, these H II regions are ionized by radiation and not by collision, since in the latter case we should expect considerably higher electron temperatures.

Rougoor: Are the OH results shown based on the observations of summer 1964, or has a new survey been made?

Robinson: The contour diagram in the (l, V) plane presented by Kerr (Figure 10 of Paper 42) is derived from new observations made in May and July 1965 and in May 1966. At 1667 MHz, R. X. McGee and I have observed on a 5′ grid over about 3° in longitude and 1° in latitude. The observations of 1964 were on a 10′ grid. In the new measurements a select grid of points has also been observed at 1612, 1665 and 1720 MHz.

Davies: There is an extended absorbing cloud of neutral hydrogen covering the galactic-centre region. Can this be associated with the low-velocity OH absorption in the galactic-centre source? I am not sure whether the velocity of the hydrogen is -5 or $+5$ km/sec.

H. van Woerden: The absorbing hydrogen has a velocity of $+5$ km/sec.

Weaver: This velocity disagrees with that of the OH feature. Therefore, no association seems possible.

F. J. Kerr: The difference between the velocities of the low-velocity absorption dips for H and OH may well be due to the hydrogen being in two main features (e.g. two spiral arms), only one of which produces OH absorption. A diagram showing the latitude variation of the hydrogen at longitude zero does in fact suggest that there are two hydrogen components at different velocities with different latitude widths.

*These sources are identical with those denoted G 0·2 0·0 and G 0·7 0·0 by Lequeux in Paper 68, cf. the footnote on page 397.—*Editor.*

I.A.U. Symposium no. 31, 1967

Chapter II E

The Origin of the Galaxy

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'*All elliptical galaxies look much the same. Why?*'
D. Lynden-Bell, in Paper 44

44. FORMATION OF THE GALAXY

(Introductory Report)

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ABSTRACT

From observations it is deduced that the disk and halo were formed about the same time and that most of the previously gaseous Galaxy became stars then. Dimensional analysis indicates that the flattening of a galaxy is related to its energy, E, angular momentum, $\mathbf{H}$, and mass, M, by the dimensionless number $-2E\mathbf{H}^2/G^2M^5$. Emphasis is placed on the binding energy, $-E$, and the energy loss mechanisms of the proto-galaxy, with the aim of explaining Fish's relation $-E \propto M^{3/2}$.

Free-bound and free-free emission of hydrogen leads to rapid cooling of proto-galaxies, and dynamical collapse ensues, in which gravitational potential energy is converted into kinetic energy of collapse. As the system becomes flat, this energy is dissipated in violent shocks, behind which zones some 10 to 20 pc thick reach temperatures of $10^{6.5}$ °K and emit strongly in the X-ray region and the ultraviolet. If surrounded by more than a fraction of a gram per cm^2, the X-rays will be trapped within the system and eventually converted into Balmer lines, which escape, and Lyman α, which is trapped. About half the total energy of collapse may be left in Lyman α, and it is possible that the system may bounce on this light energy.

The readily observed surface brightnesses of galaxies are related to surface densities by the relationship: magnitude 20 per (sec of arc)^2 = 1·5 gram cm^{-2}, for an assumed mass-to-light ratio of 10.

1. OBSERVATIONAL INFORMATION

Certain pertinent questions on the origin of the Galaxy can be answered from observations. Did the Galaxy form all at once on a time scale of $10^{8.5}$ years, or gradually by accretion on a time scale of $10^{9.5}$ years? Are the old disk stars and the halo stars of much the same age, or were some halo stars formed later by explosion from the galactic nucleus? What proportion of all the material became stars during the Galaxy's original great burst

of star formation? Were most of the chemical elements formed before or after the formation of the Galaxy?

In answering these questions I shall lean on the work of Dixon (1965, 1966), who in turn uses the work of Eggen (1962, 1964; Eggen *et al.* 1962), the Cape observers (Evans *et al.* 1957, 1959, 1964; Cousins and Stoy 1962), Sandage (1957, 1962), and many others back to Miss Roman (1955).

Since the theory of the evolution of mixed stars disagrees with the form of observed HR-diagrams, the outsides of dwarf stars probably display the unmixed chemical composition of the material from which those stars were born. By concentrating our attention on groups of stars with 'old' HR-diagrams, whose turn-off points are towards the red (around G0), we may find the composition of old material. This varies from the extreme metal-poverty of some globular clusters and high-velocity stars to the comparative metal-richness of the old galactic cluster NGC 188.

In the two-colour diagram metal-rich dwarfs lie on the same sequence as the Hyades, but, at least for spectral types F and G, the paucity of ultraviolet absorption lines in metal-poor stars leads to an ultraviolet excess of such stars with respect to the Hyades. If the metals were slowly subtracted from the atmosphere of a Hyad, it would describe a *metals track* moving away from the Hyades sequence in the two-colour diagram. Eventually it would reach the *no-metals sequence*, on which stars with no metals in their atmospheres would lie. By a study of dwarf stars with velocities greater than 100 km/sec with respect to the Sun, Dixon finds that there are no such stars to the left of a particular metals track (Figure 1). Evidently there are no very-high-velocity dwarfs of earlier spectral type, because all the high-velocity stars were formed some 10^{10} years ago and such dwarfs would have evolved into giants etc. by now. We shall call the metals track bounding the region of the two-colour diagram occupied by high-velocity stars the *galactic-age metals track* or GAM track. Dixon now turns our attention towards stars of progressively lower velocities and we see that, although the region to the left of the GAM track is populated by some stars, there is a discontinuity in the numbers between the two sides of the GAM track. He interprets this discontinuity by saying that it represents the fraction of stars that were born in the short period of rapid star formation associated with galactic birth pangs. The discontinuity decreases with decreasing $|W|$-velocity of the stars considered. After suitable weighting for observational selection, Dixon finds two thirds of the dwarfs in a cylinder through the Sun were formed in this period.

This result is in good agreement with two independent sources of evidence.

1. The number of external galaxies observed with a mass fraction of neutral atomic-hydrogen gas greater than 20% is quite small, and fractions greater than 30% are very rare. If we believe that some galaxies are forming today, this is weak evidence that the greater part of the gas turns into stars during a short initial period of star formation.

2. Star-made metals are synthesized in massive stars and ejected into the interstellar gas only some 10^7 years or so after the star's formation. Since this is short compared with the $10^{8.5}$ years which the galactic birth pangs are estimated to have lasted (Eggen *et al.* 1962), one can consider the massive stars as producing metals almost instantaneously. If two thirds of all the star formation occurred in this period, we would expect two thirds of all the star-made metals to be present at the end of it. The fact that the oldest galactic clusters are hardly significantly metal-deficient therefore fits in naturally, provided we believe that almost all metals are star-made within the Galaxy.

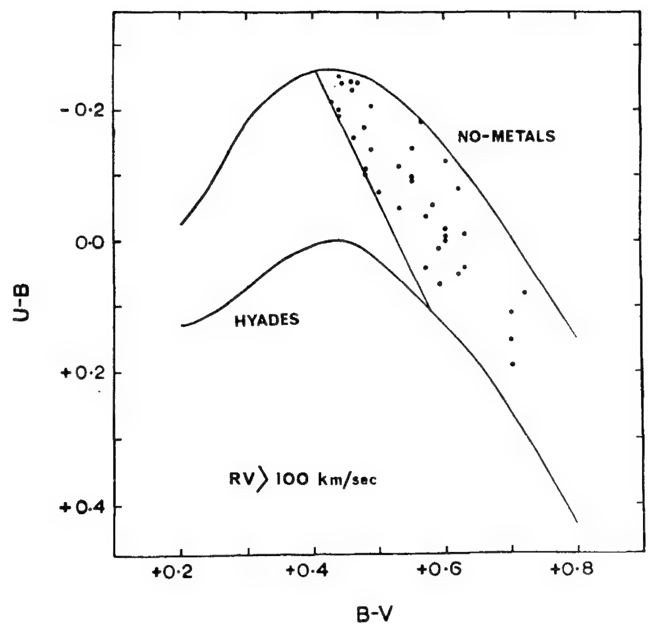

FIG. 1. The two-colour diagram for main-sequence stars with radial velocities above 100 km/sec (Dixon 1965). Only single stars within 100 pc are included. Reproduced by kind permission of Dr M. E. Dixon. The diagonal line is the GAM track.

Returning to our questions: The Galaxy probably formed on the shorter time scale; otherwise the discontinuity in the numbers of stars across the GAM track would be blurred into an increased gradient. This point requires further study with very accurate photometry of more stars, to establish the position and sharpness of the discontinuity. The fact that its position is the same for disk and halo stars establishes that *to within observational accuracy* they are of the same age. The evidence from metal abundances indicates that the disk stars were made just after the halo stars, and that the metals were formed in the Galaxy.

If stars in the halo have very little helium, the discontinuity in the star numbers should not occur along a metals track but along a modified track bent to the right at the bottom end. This is because helium-normal, metal-normal stars evolve faster and therefore have redder turn-off points than helium-poor stars.

Finally the decrease in the size of the discontinuity with decreasing $|W|$-velocity may be interpreted as a dilution of old stars in successively larger numbers of younger stars, which are concentrated more and more closely to the galactic plane. We probably have evidence here for a gradual thinning of the disk of interstellar gas as the Galaxy grew older. Edge-on extragalactic systems containing many young stars likewise seem to have less well-defined galactic planes than 'older' systems.

2. THEORY

We now turn our attention to the theory of galaxy formation. A complete theory must explain:

(1) the total masses and total angular momenta of galaxies;
(2) the overall sizes and shapes of galaxies;
(3) the distribution of mass and angular momentum within galaxies;
(4) the metal abundances of galaxies;
(5) the numbers of globular clusters, their distribution, and the observed correlation of motions and compositions of the high-velocity stars (Eggen *et al.* 1962);
(6) the *detailed* structure of galaxies, spiral arms in barred and unbarred galaxies, the gas distribution, etc.

Some of the observational facts may be systematized into approximate observational laws. Prominent among these is the discovery by Fish (1964) that the potential energies of elliptical galaxies are proportional to the three-halves powers of their masses. Preliminary investigations indicate that globular clusters and the central bulges of spiral galaxies also fit the same relation. In practice we may define an effective radius, R, such that

$$GM^2R^{-1} = -V \propto M^{3/2}. \tag{1}$$

Fish's law is then seen to relate the size of an elliptical galaxy to its mass.

In a similar fashion the laws of Hubble and of De Vaucouleurs (1953) give good fits to the observed light distributions of elliptical galaxies. The flattening of the isophotes is approximately independent of the isophote for any one elliptical galaxy, but a somewhat more detailed picture may be found from Van Houten's (1961) work. Mestel (1963) has pointed out that the assumption that the angular momentum of each elemental ring of galaxy has been preserved since some epoch at which it was roughly a uniform-density sphere or spheroid, leads to angular-momentum distributions like those of spiral galaxies. Crampin and Hoyle (1964) have found this distribution directly in a number of cases. This correspondence might be taken as very weak evidence that transport of angular momentum by magnetic fields has not been an inefficient process in the case of spiral galaxies.

Integrated spectra show that the larger elliptical galaxies are not deficient in metals like globular clusters, although the small dwarf ellipticals are deficient. Mass-to-light ratios indicate very large proportions of red dwarfs in the larger ellipticals.

Voroncov-Vel'jaminov (1966) points out that the number of globular clusters associated with a galaxy does not vary systematically with galactic mass or type.

Some of the above facts will be explainable in terms of the stellar dynamics of a galaxy, others will be dependent on pre-stellar conditions. We now show by a dimensional analysis that the overall size and shape are determined by pre-stellar conditions. In stellar dynamics the total energy, E, is conserved, as well as the total mass, M, and total angular momentum, $\mathbf{H}$. From the virial theorem we have at equilibrium

$$2T + V = 2E - V = 0. \tag{2}$$

So

$$-\frac{GM^2}{R} = 2E \qquad \text{or} \qquad R = \frac{GM^2}{-2E}\,. \tag{3}$$

Thus, for a given mass, the size of the equilibrium is determined only by the binding energy, that is, by the energy lost while the system is gaseous. The dimensionless parameter made from $\mathbf{H}$, M, E and the constant of gravity G is

$$\lambda = \frac{-2E\mathbf{H}^2}{G^2M^5} \quad . \tag{4}$$

Small λ corresponds to small $\mathbf{H}$ or to very little binding energy; such systems are normally round. Very flat systems have their kinetic energy in the form of rotation, so from the virial theorem we have

$$2T = -V = -2E, \tag{5}$$

or roughly

$$\frac{\mathbf{H}^2}{MR^2} \approx \frac{GM^2}{R} = -2E, \tag{6}$$

which gives $\lambda \approx 1$. So for a system of given total mass and total angular momentum both the size, R, and the shape parameter, λ, are determined by the binding energy. Theories of galaxy formation should therefore be directed towards determining this energy loss. Fish has already pointed out that this relationship can be written in the suggestive form

$$MR^{-2} = \text{const} \approx 2 \text{ gram/cm}^2. \tag{7}$$

Both the dimensions and the value suggest a single-particle opacity as being the determining factor behind this law.

Consider a mass $M = 2 \times 10^{44}\, m$ gram of hydrogen, with an effective radius of $R = 100\, r$ kpc $= 10^{23.5}\, r$ cm. From the virial theorem the temperature required for equilibrium is

$$T = 2 \times 10^5\, m/r \text{ °K}. \tag{8}$$

Knowing the density and assuming this temperature we can calculate the energy loss due to free-free and free-bound emission, and hence the rate of contraction, assuming the system remains secularly in equilibrium. When the velocity demanded by this contraction is comparable to the velocity of free fall under gravity, the quasi-static model becomes inconsistent and dynamical collapse ensues. If we take a cooling rate of $10^{-23}\, n^2$ erg cm^{-3} sec^{-1}, roughly appropriate for the range $10^4 < T < 10^6$ °K (Weymann 1966), then the rate of energy loss, $\dot{E}$, is about $10^{42}\, m^2\, r^{-3}$ erg sec^{-1}. Putting

$$\dot{E} = \tfrac{1}{2}GM^2R^{-2}\dot{R} \tag{9}$$

from the equilibrium virial theorem leads to a contraction rate $\dot{R} = -700\, r^{-1}$ km/sec. By contrast the free-fall contraction rate is

$$\dot{R} = -100\, m^{1/2} r^{-1/2} \text{ km/sec}. \tag{10}$$

It is evident from these figures that our postulated quasi-static contraction can only be set up at enormous radii that are quite unphysical, and that the gravitational contraction is unable to supply the heat required to keep the gas hot. Although cosmic-ray heating and magnetic pressure are more serious contenders for the proto-galaxy's means of support (Ginzburg 1966), order-of-magnitude calculations indicate that the most probable evolution of our proto-galaxy is the cooling of the gas and dynamical collapse

under gravity. As the galaxy attains something approaching its present size, the high density and low temperature provide excellent conditions for star formation. It is possible that some halo stars and globular clusters formed then, but only a small fraction of the galaxy can have condensed into stars at this stage. Before it forms the bulk of the stars, the galaxy must lose its binding energy. At the stage we have envisaged this energy is still in the material as the kinetic energy of collapse. Unopposed collapses are subject to flattening instabilities (Lynden-Bell 1964, 1965; Lin *et al.* 1965). These are only suppressed if the accelerations are less than two-fifths of their free-fall values. We shall very arbitrarily (Lynden-Bell 1964, 1965) assume here that flattening occurs along the rotation axis, and that the final stages of collapse can be represented as the one-dimensional collision of two gas clouds each moving with 300 km/sec towards the galactic plane. I am indebted to Miss Storer for working out the details of the resulting shocks. These shocks form at the interface and propagate outwards at about 100 km/sec. They are followed by regions some 10 to 20 parsec thick in which the temperature achieves values of order $10^{6\cdot 5}$ °K. There remains behind these regions a high-density, low-temperature region which is presumably the primary seat of star formation in the galaxy. The collapsing clouds are initially neutral, due to their high recombination rate. The X-rays and ultra-violet emitted by the $10^{6\cdot 5}$ °K regions are absorbed, provided the optical depth is greater than a small fraction of a gram per cm^2. Large regions of galaxies have greater surface densities than this, as may be seen directly since a brightness of the 20th magnitude per square second of arc is equivalent to 1·5 gram per cm^2, at a mass-to-light ratio of 10. The subsequent evolution of the optically thick case is an unsolved problem; some of the energy escapes in the Balmer lines and in forbidden lines of other elements, but quite a large fraction is trapped as Lyman α within the system. It is our hope to show that for surface densities greater than 1 gram/cm^2 the system will bounce on its light energy. It may then be possible to explain Fish's law, and understand why systems and parts of systems which have surface densities greater than this are almost invariably round rather than flat.

Two further points should be made.

1. A study of absolutely cold collapse shows that regions of higher density condense on a more rapid time scale than other regions. This leads to the formation of condensation nuclei, which run away to very high density before the main body of the galaxy has had time to collapse. This may be related to the formation of galactic nuclei and to the violent events with which those systems are associated.

2. I would like to stress again some points made by Field (1964). Not only are the binding energies of the larger ellipticals in the range needed for the violent radio outbursts, $\sim 10^{61}$ erg, but the rate at which this binding energy must have been radiated is of the order of 10^{45} erg/sec. Any gravitating system of binding energy $\frac{1}{2}GM^2R^{-1}$ must emit at least half that energy during the last halving of its radius, because the gravitational energy does not appear till then. It is natural to say that this energy must have been emitted on the time scale of free-fall contraction by that amount. The resulting formula for the rate of radiation is

$$-\dot{E} = \frac{1}{2}\frac{GM^2}{R}\left(\frac{GM}{R^3}\right)^{1/2} = \frac{1}{2G}\left(\frac{GM}{R}\right)^{5/2} = 10^{42}\, v_{100}^5 \text{ erg/sec}, \qquad (11)$$

where v_{100} is the present internal velocity measured in units of 100 km/sec. The formation of clusters of galaxies for which $v_{100} = 10$ must have been a spectacular event indeed!

Field also mentioned the importance of supernovae as an energy source of the contracting galaxy, and the interesting problem of statistical stellar dynamics in a recently formed non-steady galaxy. The latter problem has received considerable attention (Hénon 1964, 1966; Lecar, 1966*a*, 1966*b*; Lynden-Bell 1966).

REFERENCES

Cousins, A. W. J., Stoy, R. H. 1962, *R. Obs. Bull.*, no. 64.

Crampin, D. J., Hoyle, F. 1964, *Astrophys. J.*, **140**, 99.

De Vaucouleurs, G. 1953, *Mon. Not. R. astr. Soc.*, **113**, 134.

Dixon, M. E. 1965, *Mon. Not. R. astr. Soc.*, **129**, 51.

Dixon, M. E. 1966, *Mon. Not. R. astr. Soc.*, **131**, 325.

Eggen, O. J. 1962, *R. Obs. Bull.*, no. 51.

Eggen, O. J. 1964, *Astr. J.*, **69**, 570.

Eggen, O. J., Lynden-Bell, D., Sandage, A. R. 1962, *Astrophys. J.*, **136**, 748.

Evans, D. S., Menzies, A., Stoy, R. H. 1957, *Mon. Not. R. astr. Soc.*, **117**, 534.

Evans, D. S., Menzies, A., Stoy, R. H. 1959, *Mon. Not. R. astr. Soc.*, **119**, 638.

Evans, D. S., Laing, J. D., Menzies, A., Stoy, R. H. 1964, *R. Obs. Bull.*, no. 85.

Field, G. B. 1964, *Astrophys. J.*, **140**, 1434.

Fish, R. A. 1964, *Astrophys. J.*, **139**, 284.

Ginzburg, V. L. 1966, *Soviet Phys. JETP* (in press).

Hénon, M. 1964, *Ann. Astrophys.*, **27**, 83.

Hénon, M. 1966, Quatorzième Colloque International d'Astrophysique, Liège (in press).

Lecar, M. 1966*a*, IAU Symposium, no. 25, *The Theory of Orbits in the Solar System and in Stellar Systems*, Ed. G. Contopoulos, p. 46, Academic Press, London.

Lecar, M. 1966*b*, Quatorzième Colloque International d'Astrophysique, Liège (in press).

Lin, C. C., Mestel, L., Shu, F. H. 1965, *Astrophys. J.*, **142**, 1431.

Lynden-Bell, D. 1964, *Astrophys. J.*, **139**, 1195.

Lynden-Bell, D. 1965, *Mon. Not. R. astr. Soc.*, **129**, 299, see p. 303.

Lynden-Bell, D. 1967, *Mon. Not. R. astr. Soc.*, **136**, 101.

Mestel, L. 1963, *Mon. Not. R. astr. Soc.*, **126**, 553.

Roman, N. G. 1955, *Astrophys. J. Suppl. Ser.*, **2**, 195.

Sandage, A. R. 1957, *Astrophys. J.*, **125**, 422.

Sandage, A. R. 1962, *Astrophys. J.*, **135**, 333 and 349.

Van Houten, C. J. 1961, *Bull. astr. Inst. Netherl.*, **16**, 1.

Voroncov-Vel'jaminov, B. A. 1966, *Soviet Astr.*, **10**, 184 (1966, *Astr. Zu.*, **43**, 231).

Weymann, R. 1966, *Astrophys. J.*, **147**, 887.

NOTE ADDED IN PROOF

It now seems likely that helium is not primordial but was made with the galaxy. The energy produced in making the bulk of the helium from hydrogen is 10^{63} ergs which must have been emitted at a rate of $3 \cdot 10^{47}$ ergs/sec for 10^8 years. Since the binding energy of the galaxy is only about 10^{58} ergs it is difficult to make models of a forming galaxy which do not explode and shatter into pieces. Perhaps galaxies are only such pieces of larger bodies. See e.g.:

Sargent, W. L. W., Searle, L. 1966, *Astrophys. J.*, **145**, 652.

Lynden-Bell, D. 1967, *Observatory*, **87**, no. 959.

Arp, H. 1967, *Astrophys. J.*, **148**, 321.

Discussion

S. B. Pikel'ner: As shown by L. M. Ozernoj (1962, in *Sbornik naučnyh rabot studentov MGU*, p. 33), the amount of fragmentation in a condensing cloud depends on the ratio of the cooling time to the time of contraction in free fall. If this ratio is small, the cloud divides into many parts; if it is about 1, the number of fragments is small; for large ratios, the cloud does not divide.

D. Lynden-Bell: I agree that this is what theory gives; but if you don't lose the binding energy, the system will end up too big.

I.A.U. Symposium no. 31, 1967

Chapter II F

High-Velocity Gas

CHAIRMAN: M. Schmidt

(Mount Wilson and Palomar Observatories, Carnegie Institution of Washington and California Institute of Technology, Pasadena, California, U.S.A.)

'Our Galaxy may have a bridge and a tail.'
S. B. Pikel'ner, in the Discussion (Paper 50)

'I think it may be time to bury the dense intergalactic medium discussed by Sciama under the names of Kahn and Woltjer.'
'That's a number that crept into the literature, and now it's apparently creeping out again.'
L. Woltjer and G. R. Burbidge,
in the Discussion (Paper 50)

45. MOTIONS OF NEUTRAL HYDROGEN AT HIGH LATITUDES

(Introductory Report)

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(Sterrewacht, Leiden, Nederland)

ABSTRACT

Earlier investigations have shown that there is a preponderance of negative velocities in the hydrogen gas at high latitudes, and that in certain areas very little low-velocity gas occurs. In the region $100° < l < 250°$, $+40° < b < +85°$, there appears to be a disturbance, with velocities between -30 and -80 km/sec. This 'streaming' involves about $3000\ (r/100)^2$ solar masses (r in pc). In the same region there is a low surface density at low velocities ($|V| < 30$ km/sec). About 40% of the gas in the disturbance is in the form of separate concentrations superimposed on a relatively smooth background. The number of these concentrations as a function of velocity remains constant from -30 to -60 km/sec but drops rapidly at higher negative velocities. The velocity dispersion in the concentrations varies little about 6·2 km/sec. Concentrations at positive velocities are much less abundant.

About twenty isolated features or 'clouds' have been found in the velocity range − 250 to − 80 km/sec; they are concentrated in the region around $l = 120°$, $b = +50°$. No systematic pattern is present in the velocities as function of position, although there are indications of cloud complexes extending over several square degrees. The surface densities of the clouds are about half that of the concentrations and they have higher velocity dispersions. The mass involved is about 60 $(r/100)^2$ solar masses (r in pc).

1. INTRODUCTION: SUMMARY OF EARLIER WORK

The properties of the neutral hydrogen away from the galactic plane have been the object of observational surveys and analyses at various observatories. The principal ones are those at DTM (Erickson *et al.* 1959, Erickson and Helfer 1960, Helfer 1961), Jodrell Bank (Davies 1960), Sydney (McGee and Murray 1961, McGee *et al.* 1963), and Groningen-Dwingeloo (Blaauw 1962, Van Woerden *et al.* 1962, Takakubo 1963, Takakubo and Van Woerden 1966, Takakubo 1967, Habing 1966). The DTM, Jodrell Bank and Sydney surveys spanned virtually the whole sky accessible from these observatories and dealt mainly with the distribution of surface brightness and of peak velocities. The Groningen-Dwingeloo survey was confined to a grid at the intermediate galactic latitudes to 10° to 25° and aimed primarily at a determination of the distributional and kinematical properties of the individual gas clouds.

These early investigations showed that there is, in almost all directions, a preponderance of negative velocities (with respect to the local standard of rest); that in certain high-latitude areas very little low-velocity gas occurs; and that at the intermediate latitudes the velocities between −20 and −80 km/sec are concentrated between longitudes 95° and 140°, indicating the occurrence of a gas stream approaching the Sun from a direction about $l = 115°$. All these phenomena occur in both the northern and the southern hemisphere, but are most pronounced in the northern one.

Regional studies have been carried out by various authors, as summarized elsewhere (Van Woerden, Paper 1 in this volume). Of particular importance are those by Dieter (1964, 1965) covering the northern and southern galactic polar caps; these revealed, apart from the systematically negative moderate velocities, clouds with high negative velocities, up to −88 km/sec. High-velocity clouds at high latitudes had first been detected in 1962 by Muller *et al.* (1963).

The present paper reviews, in a preliminary form, more recent developments, based on Dwingeloo observations covering the range of velocities −250 to +150 km/sec.

2. RECENT AND CURRENT DWINGELOO SURVEYS

Blaauw and Tolbert (1966) have recently published results of a 1963 Groningen-Dwingeloo survey, based on observations in a wide grid at latitudes $|b| > 30°$, in the velocity range −70 to +70 km/sec. The preponderance of negative velocities at high positive latitudes, noted by earlier observers, appeared to have the character of local disturbances of the hydrogen layer in the solar neighbourhood, and suggested the existence of an inflow of gas from a direction between 110° and 180° longitude, and with latitude around +15°. These high-latitude phenomena appeared to be closely connected with the intermediate-latitude streaming noted in the earlier Groningen-Dwingeloo work.

Hulsbosch and Raimond (1966) have reported Leiden-Dwingeloo work on the higher velocities (roughly $|V| = 70$ to 200 km/sec), based on observations in 1963–65 at $|b| > 20°$. They list 30 positions where peaks were found in the profiles; the velocities of these peaks are all negative, but otherwise cover the entire range just mentioned. Hulsbosch and Raimond observed regional, dense grids for the study of 'complexes', i.e. areas of adjacent positions with peaks at comparable velocities. They discuss a few high-velocity objects in some detail. Most of the high-velocity peaks appear to be concentrated in the region $70° \leqslant l \leqslant 170°$, $+30° \leqslant b \leqslant +50°$.

The observations for these Dwingeloo surveys, and details of the instrumental properties, have been published by Muller *et al.* (1966).

These researches are now being extended by means of new observations, conducted in 1965 and 1966 by Muller, Fejes, Hulsbosch, Raimond and Tolbert. A preprint on work by Tolbert and Fejes was distributed at the Noordwijk Symposium. In the analyses a certain degree of separation of the high-velocity features on the one hand, and the intermediate-and-low-velocity features on the other hand, has been maintained in dividing the work between Leiden and Groningen. For practical purposes, we shall define three velocity domains as follows:

Low velocities	$0 < \|V\| < 30$ km/sec
Intermediate velocities	$30 < \|V\| < 80$ km/sec
High velocities	$80 < \|V\| < 200$ km/sec

Figure 1 sketches, in a schematic fashion, the nature of the surveys available at the time of the Symposium. It indicates the bandwidths used, the velocity ranges and sky areas covered, and the total numbers of positions observed. We shall discuss the low-and-intermediate-velocity domain and the high-velocity domain separately.

3. THE LOW AND INTERMEDIATE VELOCITIES

a. Surface densities N_H

Figure 2 shows the distribution of the integrated numbers, N_H, of neutral hydrogen atoms per cm^2, for the low-velocity range. The diagram is centred on the galactic longitude 120°; this holds also for most of the following diagrams. Around this longitude the most conspicuous features in the various velocity domains occur. (It also is, approximately, the longitude of the northern equatorial pole.) Notice the scarcity of low-velocity gas at latitudes $b > +40°$, between longitudes 50° and 220°.

We compare this plot to similar ones for the intermediate negative-velocity range, Figure 3, and for the intermediate positive-velocity range, Figure 4. The region which has lowest surface density at the low velocities shows, in general, excess surface density for the intermediate negative velocities. At the positive intermediate velocities, we find generally low N_H, but there are some notable spur-like exceptions, such as those at $l = 70°$ and 310° in the northern hemisphere.

Averaging over the region where the excess densities in the velocity range -30 to -80 km/sec are most pronounced ($l = 140°$ to 280°, $b = +60°$ to $+85°$; and $l = 90°$ to 150°, $b = +35°$ to $+55°$), we find for this velocity range $\langle N_H \rangle = 6{\cdot}3 \times 10^{19}$ cm^{-2}, which is about 40% of the mean integrated value over all velocities, $\langle N_H \rangle = 16 \times 10^{19}$ cm^{-2}

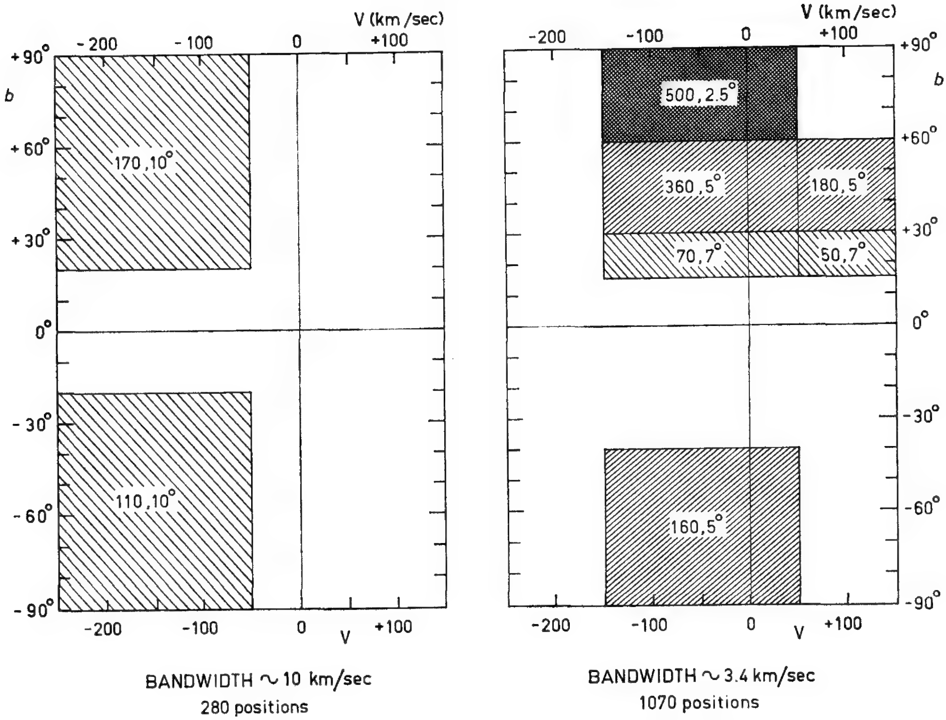

FIG. 1. Schematic representation of Dwingeloo 21-cm surveys carried out in 1965 and 1966. At right: Groningen programme (Tolbert and Fejes); at left: Leiden programme (Hulsbosch and Raimond). Numbers in various compartments are approximate number of points measured, and spacing of grid (sometimes incompletely covered). All longitudes observable from Dwingeloo are included. The Leiden survey of high-velocity clouds comprises, moreover, observations made in 1963 at 210 positions with bandwidth 3·4 km/sec, and also regional, denser grids. The beamwidth of the Dwingeloo telescope is 0°6.

The total mass involved in the velocity range -30 to -80 km/sec, in this area of about 2000 square degrees, is estimated at 3000 $(r/100)^2$ solar masses, r (in pc) being the root-mean-square of the distances of the hydrogen involved in this region.

b. Velocity distribution

Details of the velocity distribution can be exhibited in the way shown in Figures 5 and 6. These contour diagrams show lines of equal brightness temperature as a function of galactic latitude and velocity, for a given section through the north galactic pole. Thus, Figure 5 refers to the latitudes $+20°$ through $+90°$ to $+20°$, for longitudes 140° and 320°, and Figure 6 does the same for $l = 50°$ and 230°. Notice the deficiency of low-velocity hydrogen at high latitudes in both diagrams, and the corresponding presence of intermediate-velocity peaks at the same latitudes, and, sometimes, also at latitudes where the low-velocity emission does occur. The preprint by Tolbert and Fejes contains the

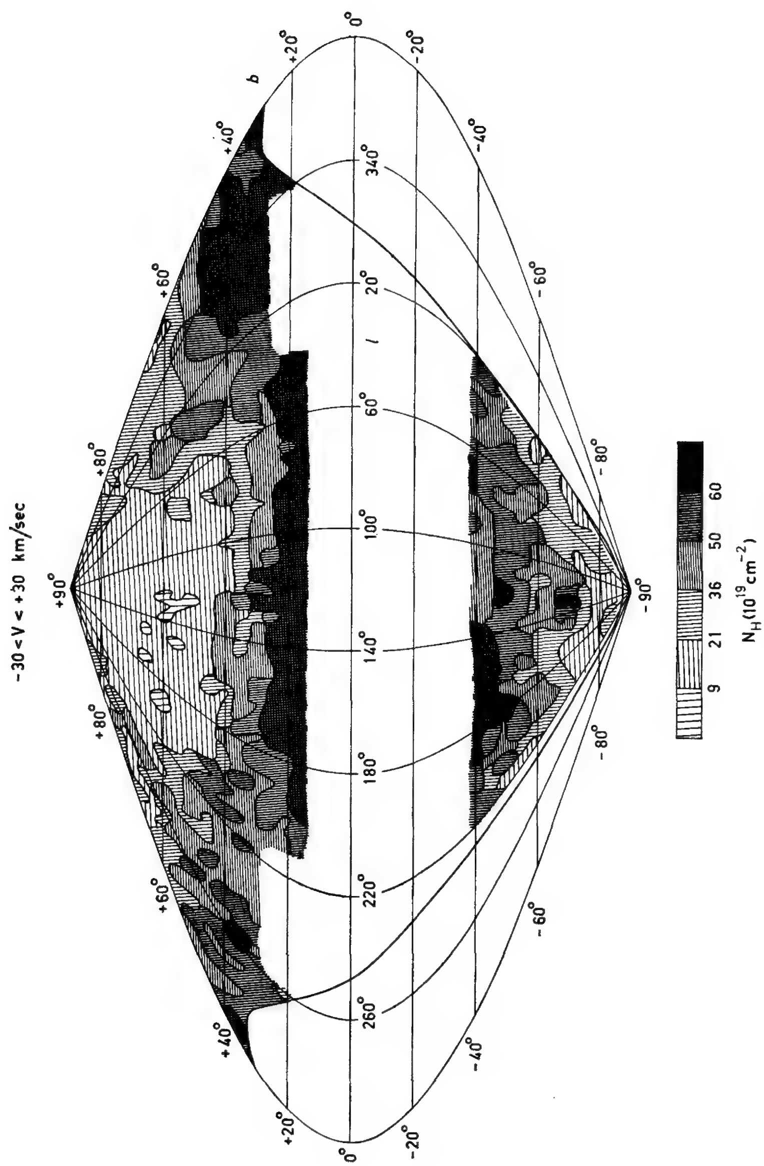

FIG. 2. Surface density distribution, N_H (atoms per cm^2), integrated over the velocities -30 to $+30$ km/sec. The curve bordering the area surveyed corresponds roughly to declinations having maximum altitudes of about 10° at Dwingeloo.

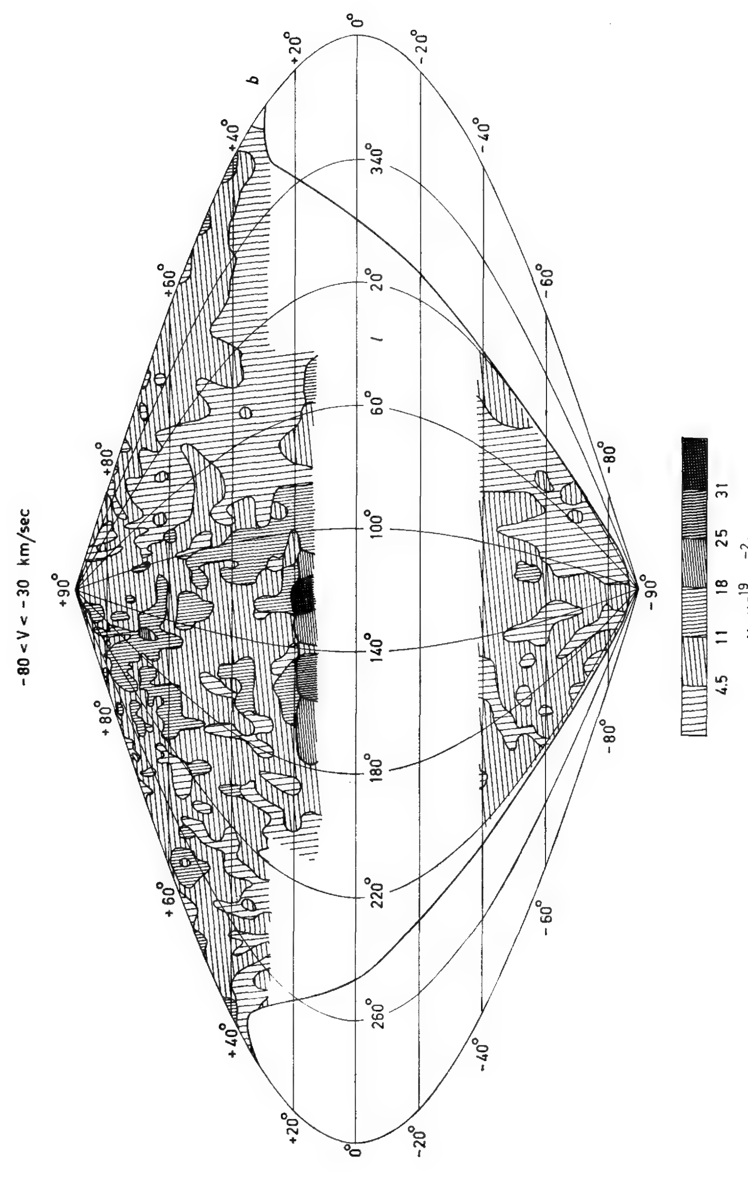

FIG. 3. Surface density distribution, N_H (atoms per cm²), integrated over the velocities − 30 to − 80 km/sec. Cf. Figure 2.

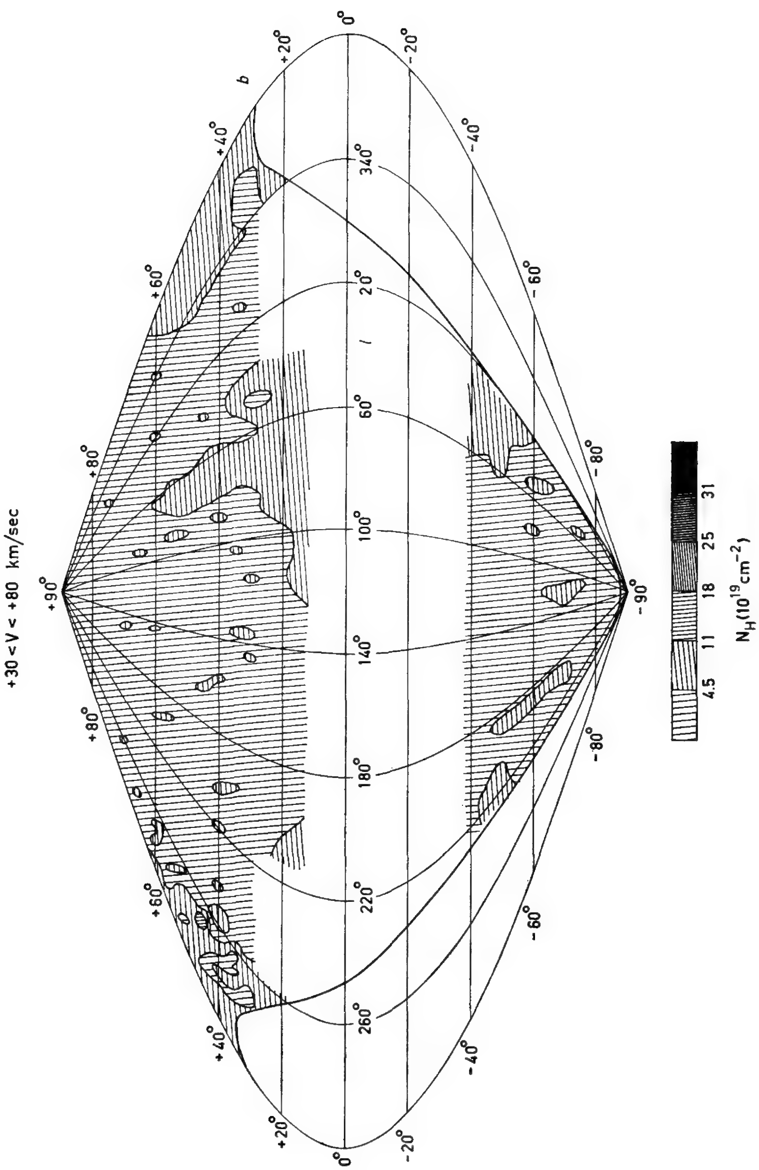

FIG. 4. Surface density distribution, N_H (atoms per cm^2), integrated over the velocities + 30 to + 80 km/sec. Cf. Figure 2.

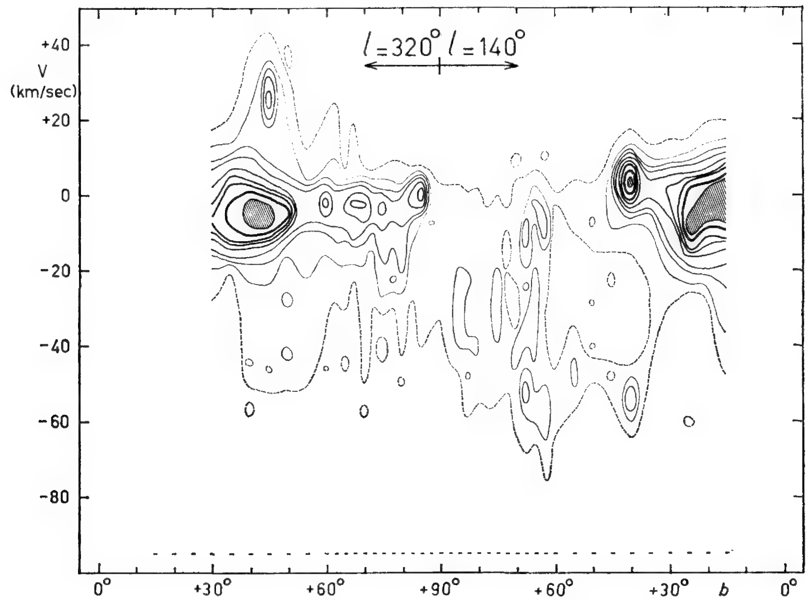

FIG. 5. Contour diagram of brightness temperatures T_b (V, b) for the section through the galactic pole and longitudes 140° and 320°. The dashed contour represents $T_b = 1$ unit (≈ °K); solid lines indicate T_b = 2, 3, 4, 6, 8, 10, and 14 units.

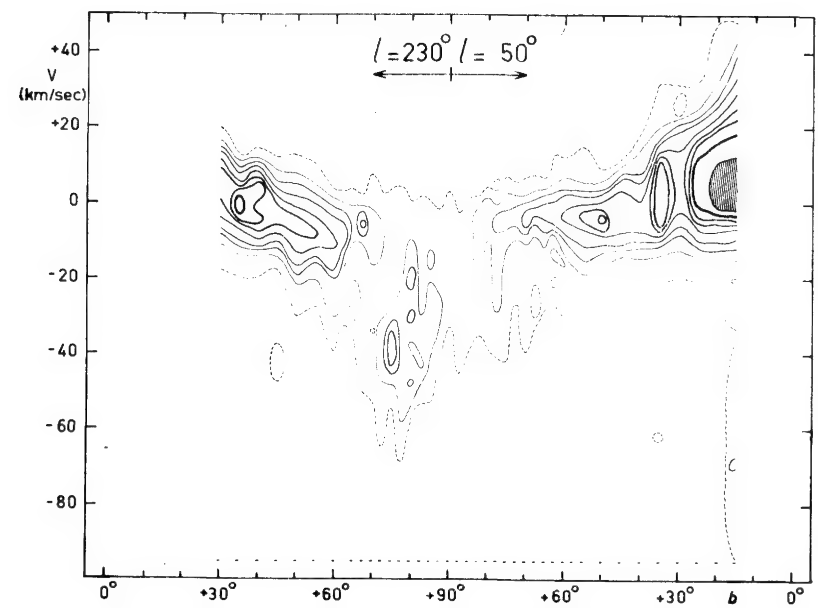

FIG. 6. Same as Figure 5 for longitudes 50° and 230°.

complete atlas of such diagrams at the positive latitudes, for all longitudes $l = k \times 10°$ (k integer), and less complete diagrams for the intermediate longitudes. It also gives similar, but incomplete, diagrams for the southern latitudes. The preprint furthermore contains improved contour diagrams $T_b(V, l)$ for constant latitudes, of the kind used for the 1963 survey by Blaauw and Tolbert (1966).

c. Concentrations

In the contour diagrams $T_b(V, b)$ a number of concentrations of neutral hydrogen are apparent; examples are those at $b = +40°$, $V = -53$ km/sec, and at $b = +70°$, $V = -50$ km/sec, in Figure 5. Tolbert and Fejes list the intermediate-velocity concentrations, i.e., those having $|V| > 30$ km/sec and detached from the main low-velocity ridge. Some of their properties are summarized in Table 1, which lists, for 10 km/sec intervals of velocity, the number of concentrations counted, the mean value of N_H and the mean internal velocity dispersion. These quantities were measured by subtracting from the 'peak' in the profile the interpolated emission corresponding to the broad basis of the profile on which the peaks usually are superimposed; they must, however, be considered provisional. Only peaks exceeding 2 units (°K) of brightness temperature have been counted.

Considering first the concentrations at *negative* intermediate velocities, in the left-hand part of the table, we notice that their numbers are about constant down to -60 km/sec, and subsequently drop rapidly. The surface densities N_H remain about the same over the whole velocity range. Of special interest is the constancy of the internal velocity dispersion; its mean value is 6·2 km/sec. Also within the various velocity intervals, the deviations from this mean are quite small: $\pm$ 1 km/sec on the average.

In the velocity domain -30 to -80 km/sec, the contribution of these 'concentrations' to the average value of N_H ($6{\cdot}3 \times 10^{19}$ cm^{-2}, as mentioned before) is about $2{\cdot}6 \times 10^{19}$, i.e. about 40%; the mass contribution must be the same fraction, if the mean distance of the concentrations is the same as that of the remaining gas.

The positions in the sky of these 'concentrations' are shown in Figure 7. Notice that in *this* figure the central longitude is 200°, not 120° as in the other plots, and that it covers only a limited area of the northern hemisphere. The circle thickness indicates the velocity. Underlined concentrations are those which stand out as isolated peaks, without a low-intensity base in common with the rest of the profile. It follows from the diagram that the majority of the concentrations are imbedded in a medium with similar velocities, varying gradually over the sky. On the whole, there is little regularity in the observed pattern; perhaps the highest velocities tend to prefer the lower right-hand part of the diagram.

Figure 8 shows the positions of the *positive*-velocity concentrations of Tolbert and Fejes' list, with the exception of a few between $+30$ and $+40$ km/sec. This survey is less complete than the one for the negative velocities (see Figure 1); between latitudes $+15°$ and $+60°$, the number of points observed for positive velocities is about one-half that for the negative velocities. Yet the conclusion seems justified that positive-velocity concentrations are much less abundant than negative-velocity ones. They occur mostly at longitudes around 340° and 70°; the latter group is responsible for the 'spur' at the same longitude in Figure 4.

Some statistics of these positive-velocity concentrations are in the right-hand part of Table 1. For velocities exceeding 50 km/sec, the average N_H-numbers are much lower than those for the negative velocities. The velocity dispersions are again similar.

Table 1

Intermediate-velocity concentrations and high-velocity clouds

Upper half of table: intermediate-velocity concentrations (Tolbert and Fejes); lower half: high-velocity clouds (Hulsbosch and Raimond); both from unpublished Dwingeloo 21-cm surveys.

The numbers for high negative velocities have been reduced to the same number of observed positions as was used for the intermediate negative velocities. The numbers for positive velocities have not been scaled; they refer to a smaller number of points on the sky (see also text).

Velocity (km/sec)	Number	$10^{-19}\langle N_H \rangle$ (cm^{-2})	Dispersion (km/sec)	Velocity (km/sec)	Number	$10^{-19}\langle N_H \rangle$ (cm^{-2})	Dispersion (km/sec)
− 30				+ 30			
	37	9·4	6·1		3	9·8	6·7
− 40				+ 40			
	44	9·9	6·7		0		
− 50				+ 50			
	31	8·7	5·9		5	2·3	6·8
− 60				+ 60			
	6	8·4	5·9		2	6·6	5·7
− 70				+ 70			
	4	9·6	6·4		10	2·9	8·4
− 80				+ 80			
					4	2·7	8·1
				+ 90			
− 80							
	13	4·3	11				
− 100							
	6	4·1	10				
− 120							
	13	3·7	10				
− 140							
	8						
− 160							
	8	5·5	11				
− 180							
	2						
− 200							

4. THE HIGH-VELOCITY CLOUDS

As is shown in Figure 1, the general survey by Hulsbosch and Raimond, covering the velocities −250 to −50 km/sec, hitherto contains about 170 positions in the northern hemisphere and about 110 in the southern one. To this were added much denser, regional grids for the detailed study of cloud complexes; these are discussed by Oort in Paper 46 (Section 5). An essential feature of the Hulsbosch-Raimond survey is the large bandwidth

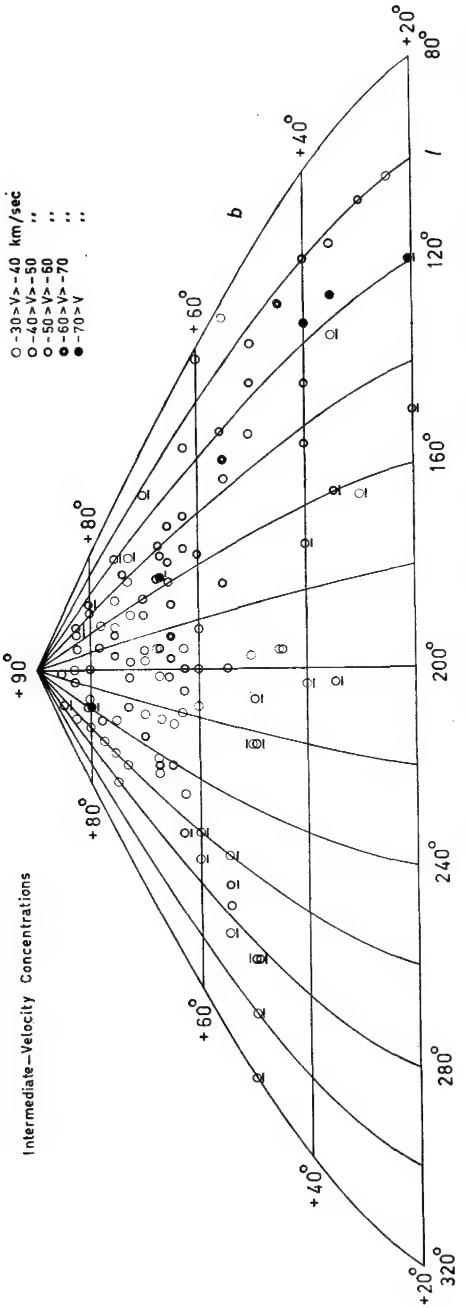

FIG. 7. Positions of the intermediate-velocity concentrations at negative velocities. Dashes indicate isolated peaks in the profiles (see text).

(10 km/sec), which allowed the detection of fainter features in the profiles than would have been possible with the bandwidth of 3·4 km/sec used for the surveys at low and intermediate velocities. In the 1963 high-velocity survey, which covered 210 positions with the velocity range $|V| < 170$ km/sec, this smaller bandwidth was used.

In the high-velocity range, there is no observable profile wing on which the peaks are superposed; they are thus isolated features of the profile. We shall call these 'clouds' rather than 'concentrations', although there is no sharp division between the two.

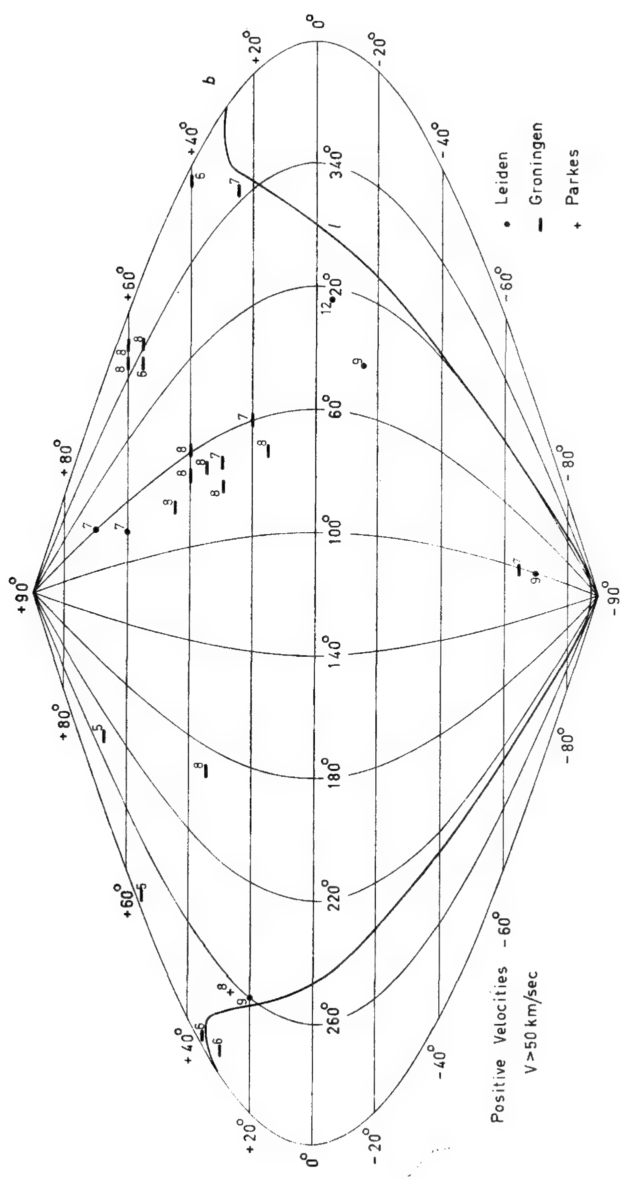

FIG. 8. Positions of the positive-velocity concentrations. Numbers by the side of the position markings indicate velocities in units of 10 km/sec. The 'horizon' lies at about 10° altitude (cf. Figure 2).

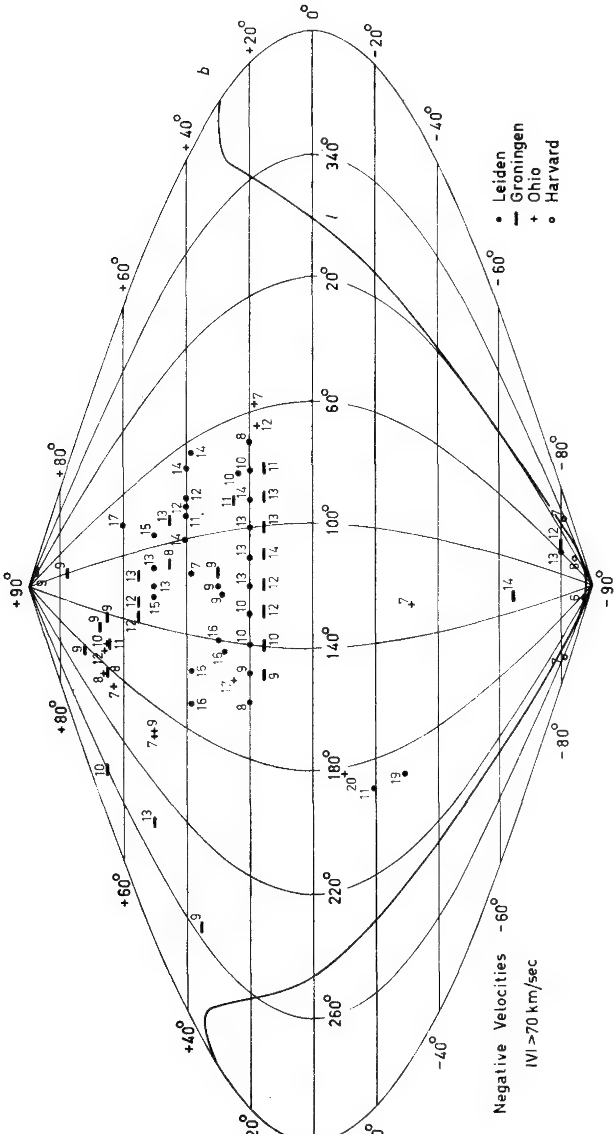

FIG. 9. Positions of the high-negative-velocity clouds found in the systematic Dwingeloo surveys and by other investigators. Absolute values of the velocities are indicated, in units of 10 km/sec.

The great majority of high-velocity clouds found so far have *negative* velocities. Figure 9 shows the positions of the high-velocity clouds found from these general surveys between -70 and -200 km/sec. The majority are remarkably concentrated in the region centred around $l = 120°$, $b = +50°$, where we also found the anomalies in the lower-velocity pattern in Figures 2 and 3. With one exception, to be discussed below, no obvious systematic run of velocities with position is apparent, but Oort shows (Paper 46, Figure 4) that there are areas of virtually constant velocity, overlapping on the sky, and giving rise

to the concept of cloud complexes. At $b = +15°$ and $+20°$, a systematic run of velocities, from $+80$ km/sec at $l = 60°$, through $+140$ km/sec at $l = 90°$, to $+80$ km/sec at $l = 160°$, does occur; this is the emission which Habing (1966) proposes to assign to a vertical extension of the Outer Arm of the Galaxy. (For a discussion of this feature, see also Lindblad, Paper 24.) Figure 9 also indicates the positions of high-velocity clouds found by Dieter (1965) and by Mathewson (private communication).

The lower half of Table 1 collects some statistics of the high-velocity clouds, similar to the data for the intermediate-velocity objects. The numbers in the second column are scaled up to expected values for an observed grid having the same density as that of the intermediate-velocity survey; the multiplication factor is about 2·5.

Comparison with the upper part of the table indicates a minimum frequency occurring about velocity -70 km/sec, so that the high-velocity clouds probably represent a real secondary maximum. Their N_H numbers are about half those in the intermediate-velocity range. The average internal velocity dispersion seems to be higher for the high-velocity clouds, but the difference cannot yet be considered well-established, in view of the different and rather provisional ways in which the two kinds of object were isolated from the profiles.

The total mass occurring in the high-velocity clouds is estimated to be about $60\,(r/100)^2$ solar masses (r in pc). If they were at the same distances as the intermediate-velocity concentrations, their mass would be about one-fifth that of the concentrations. But they may be more remote and then possess a considerably larger total mass.

ACKNOWLEDGMENT

It is a pleasure to acknowledge the collaboration with Prof. C. A. Muller and his staff at the Dwingeloo Radio Observatory, and the financial support by the Netherlands Organization for the Advancement of Pure Research (Z.W.O.).

REFERENCES

Blaauw, A. 1962, in *The Distribution and Motion of Interstellar Matter in Galaxies* Ed. L. Woltjer, W. A. Benjamin, Inc., New York, p. 48.
Blaauw, A., Tolbert, C. R. 1966, *Bull. astr. Inst. Netherl.*, **18**, 405.
Davies, R. D. 1960, *Mon. Not. R. astr. Soc.*, **120**, 483.
Dieter, N. H. 1964, *Astr. J.*, **69**, 288.
Dieter, N. H. 1965, *Astr. J.*, **70**, 552.
Erickson, W. C., Helfer, H. L. 1960, *Astr. J.*, **65**, 1.
Erickson, W. C., Helfer, H. L., Tatel, H. E. 1959, IAU Symposium, no. 9, *Paris Symposium on Radio Astronomy*, Ed. R. N. Bracewell, p. 390, Stanford Univ. Press, Stanford, Calif., U.S.A.
Habing, H. J. 1966, *Bull. astr. Inst. Netherl.*, **18**, 323.
Helfer, H. L. 1961, *Astr. J.*, **66**, 160.
Hulsbosch, A. N. M., Raimond, E. 1966, *Bull. astr. Inst. Netherl.*, **18**, 413.
McGee, R. X., Murray, J. D. 1961, *Austr. J. Phys.*, **14**, 260.
McGee, R. X., Murray, J. D., Milton, J. A. 1963, *Austr. J. Phys.*, **16**, 136.
Muller, C. A., Oort, J. H., Raimond, E. 1963, *C. r. Acad. Sci.*, Paris, **257**, 1661.
Muller, C. A., Raimond, E., Schwarz, U. J., Tolbert, C. R. 1966, *Bull. astr. Inst. Netherl. Suppl. Ser.*, **1**, 213.
Takakubo, K. 1963, *Sendai astr. Rap.*, no. 85.
Takakubo, K. 1967, *Bull. astr. Inst. Netherl.*, **19**, 125.
Takakubo, K., Van Woerden, H. 1966, *Bull. astr. Inst. Netherl.*, **18**, 488.
Van Woerden, H., Takakubo, K., Braes, L. L. E. 1962, *Bull. astr. Inst. Netherl.*, **16**, 321.

I.A.U. Symposium no. 31, 1967

46. POSSIBLE INTERPRETATIONS OF THE HIGH-VELOCITY GAS

(Introductory Report)

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ABSTRACT

After a brief summary of observational information on gas with high and intermediate velocities, the objections against several possible origins for these phenomena are reviewed. The best hypothesis appears to be an intergalactic origin, near the Local Group. The intergalactic density required if the observed high-velocity flow is a continuing phenomenon is estimated at 10 to 100 × 10^{-29} g cm^{-3}, depending on the z-distance of the intergalactic matter at the time of its deceleration by galactic gas, and on the importance of cosmic rays in this deceleration. The effects of the observed inflow of gas on galactic dynamics may be of great significance.

1. INTRODUCTION; SUMMARY OF OBSERVED PHENOMENA

In the following discussion we shall be exclusively concerned with observations outside the galactic zone, i.e. at latitudes $|b| \geqslant 10°$, and with hydrogen moving at fairly high velocity. As was done in Blaauw's preceding report (Paper 45), I shall refer to velocities of 70 km/sec and larger as high velocities, and to the velocities between 30 and 70 km/sec (or, sometimes, 80 km/sec) as intermediate ones. Unless specifically indicated, velocities are measured relative to the 'local standard of rest', which is meant to coincide with the average of the interstellar medium in the vicinity of the Sun.

The phenomena to be explained may, somewhat schematically, be summarized as follows:

(*a*) With only few exceptions all the high-velocity gas observed has a *negative* velocity.

(*b*) The high negative velocities (−70 to −200 km/sec) are almost entirely *concentrated* in the region from 60° to 200° galactic longitude and +10° to +80° latitude. Apart from the gas at +15° and +20° latitude, which displays different properties, and probably belongs to a very distant spiral arm extending to heights of a few kpc above the galactic plane (Habing 1966), there is no indication of any increase in density towards the galactic equator. The centre of the region where the bulk of the high-velocity gas appears to come from is situated around $l = 120°$, $b = +40°$.

(*c*) The gas with *intermediate* negative velocities appears generally to be concentrated in about the same region, though there may be differences in detail. At intermediate velocities the intensity of radiation is much greater than at high velocities.

(*d*) Gas of high as well as intermediate velocity is also found in the *southern* galactic hemisphere, but in much smaller amount. Again, negative velocities are much more frequent than positive ones. In a very general way the distribution in longitude and

latitude for the intermediate-velocity gas can be said to resemble that in the northern galactic hemisphere. The *high* velocities are too few to judge; but they display in any case the same characteristic of occurring up to very high latitudes. It should be remarked that the surveys at negative latitudes do not cover the region between 240° and 360° longitude, which lies at too low declinations to be observed from The Netherlands.

(*e*) The high-velocity matter has an outspoken *cloudy* structure. The velocity dispersion within each cloud is high, averaging about 10 km/sec. For details see Section 5.

(*f*) As regards the *distances* of the clouds, the only indication available comes from the observation by Münch and Zirin (1961) of interstellar Ca^+ and Na absorption lines in a score of distant early-type stars at high latitudes. From the fact that the number of interstellar components with velocities in excess of 15 km/sec increases with the distance z of the stars from the galactic plane, they infer that a fair proportion of these clouds lies between $z = 500$ and 1000 pc. There are five stars in their list with $z > 1000$ pc. Two of these each show two interstellar components with velocities in excess of 30 km/sec. The four velocities are negative, ranging from -34 to -55 km/sec. In an unpublished investigation Habing has found 21-cm emission at the same velocities in the surroundings of these stars. It thus is very probable that Münch and Zirin's observations refer to intermediate-velocity clouds of the kind we are discussing. This may then give an indication that these clouds lie at considerable distances from the galactic plane. However, it is no more than a weak indication, for Münch and Zirin's statistics rest on an extremely small sample.

The *problems* we wish to consider are:

(1) the origin of these phenomena (Section 2), and

(2) the consequences, in so far as they bear on the structure and density of the intergalactic gas, and on the distribution and dynamics of the gas in the Galaxy (Sections 3 and 4).

It is quite clear that the phenomena are extremely complex, and that we cannot hope to obtain one simple explanation.

2. THE ORIGIN OF THE HIGH-VELOCITY GAS

In a recent article (Oort 1966), a reprint of which was distributed to the participants in the Symposium, I have considered a number of possibilities, and given reasons why all the origins considered may have to be rejected except an origin in extragalactic space. In order not to complicate my report I will now only list some of the reasons why the two most likely alternatives were tentatively rejected:

Supernova shells

There is *nowhere* any Hα or $\lambda 3727$ emission.

It seems extremely improbable that such shells should be concentrated in *high galactic latitudes*.

It seems extremely improbable that this should be so in *both galactic hemispheres* and at the *same average longitude*.

The required frequency of supernova explosions appears prohibitive.

If the distances proposed by Münch and Zirin are correct, the shells are much too large for supernovae.

Superexplosion in the galactic plane

This hypothesis has been investigated at some length in the article mentioned above. Perhaps the most serious difficulty in its way is the existence of small high-velocity clouds with large internal velocity dispersions. The lifetimes of such clouds would appear to be much shorter than the times they would have needed to travel from the point of ejection to the vicinity of the Sun.

Judging from the present data I believe, therefore, that the most likely origin of the high-velocity objects is from *intergalactic space*. Here we may consider two possibilities:

(*a*) What we see are a kind of *satellites* or streamings of gas which have been *moving around the Galaxy* since its formation; satellites of the same nature as the Magellanic Clouds, only smaller. These satellites, or streams, will gradually be swept up by the Galaxy. The idea is an attractive one, but it seems untenable if we consider the consequences.

From the observations of the high-velocity gas in the northern galactic hemisphere I estimate that the original mean surface density, $\langle N_{\mathrm{H}} \rangle$, for the clouds that now have velocities between -70 and -200 km/sec, is $0{\cdot}8 \times 10^{19}$ H-atoms per cm^2. It appears likely that a good fraction of the satellite or stream has already been further decelerated, and the original value of $\langle N_{\mathrm{H}} \rangle$ must have been at least 2 or 3 times higher, or about 2×10^{19} cm^{-2}. As the internal velocity dispersions in the original satellites would have been small, their average peak brightness temperature, observed with a bandwidth of 16 kHz = 3·4 km/sec, as used in the Groningen surveys, should be about 3° K. If the satellites would have diameters of 1 kpc there should be about 10^6 of them, and several should be visible in each beamwidth. None has so far been observed.

(*b*) It thus seems necessary to assume that the observed streams come from larger distances. I would favour the idea that the Galaxy and the Andromeda Nebula are still in the process of condensation from the universe, and that what we see is *gas falling in from distances of the order of* 10^6 *pc*, rather than 10^5 pc as in the above model. (At 1 Mpc the velocity of escape from the combined mass of the Galaxy and the Andromeda Nebula is 77 km/sec. The time of free fall from a distance of 0·5 Mpc is 7×10^9 years. With extra velocities of 50 km/sec the clouds we observe now could have come from distances of the order of 1 Mpc.)

We may now ask what *velocity distribution* we should, on the present hypothesis, expect for the incoming clouds. Let us assume that the clouds originally moved with random velocities of the order of 50 km/sec, and that the Galaxy has likewise a velocity of this order. In a rough approximation the clouds would then describe hyperbolic orbits around the centre of our Galaxy. In the vicinity of the Sun the clouds approaching the centre would preponderate over those going in the opposite direction, because the latter would all have crossed the galactic plane in an earlier part of their orbit, and for about 60% this crossing would have taken place within the limits of the Galaxy, and would effectively have stopped them. Qualitatively this would account for the fact that we observe more high-velocity gas coming from longitudes opposite the centre than from the direction of the centre itself. The strong preference for the longitudes between 90° and 180° over those between 180° and 270° is the natural consequence of the fact that we observe in a co-ordinate system moving with the rotational velocity of the Galaxy, that is, in the direction of 90° longitude.

The inclinations of the original orbits on the galactic plane should be evenly distributed between 0° and 90°. In a general way this explains the absence of a relation between the directions of observation of the high-velocity clouds and the galactic equator. Clouds moving in orbits of low inclination may, moreover, not reach us because they have been stopped earlier in the galactic halo.

Though our hypothesis may thus explain some of the main features of the observed distribution of the high velocities, there can be no doubt that this distribution must be strongly influenced by the inherent large-scale unevenness of the distribution of matter in extragalactic space, as well as by the unknown mass motion of our own Galaxy. The outspoken *north-south asymmetry* in the distribution of the high-velocity clouds would, for instance, have to be attributed to these causes.

We must now consider the flow of gas carried by the high-velocity clouds. This is of interest for two reasons. One is that it furnishes information on the intergalactic density. The other is connected with the dynamics of the spiral structure in the galactic disk; judging from the present observations the flow is so large that it is likely to have considerable influence on the motions in the disk.

3. AMOUNT OF INFLOW, AND INTERGALACTIC DENSITY

Let us start by estimating the flow due to clouds with radial velocities between -70 and -180 km/sec in the north galactic hemisphere. We have available a large number of well-observed data on the surface density of hydrogen at these high velocities, down to a limit of about 2×10^{19} atoms per cm^2; from these we can make a fair estimate of the average density if the gas would be spread evenly over the entire region where high-velocity clouds have been observed. This comes out as $1{\cdot}4 \times 10^{19}$ cm^{-2}.

Before we can estimate the flow towards the galactic plane, we must know the *thickness of the layer* in which these clouds are contained. The estimate depends largely on whether we assume that they are at present being decelerated in a galactic layer extending to, say, 500 or 600 pc from the plane, or in a gaseous corona extending to several kiloparsecs. In the first case the layer in which they are situated could hardly be thicker than 500 pc, in the second case it would be likely to be a few kpc thick.

Of one thing I believe we can be certain: namely, that the clouds, or streams, have been *decelerated* by sweeping up interstellar gas. For it is this mechanism which must be responsible for the large internal velocities observed in *all* high-velocity clouds. In order to determine the relative amount of the swept-up gas, we must first estimate the original velocity with which the clouds have entered the Galaxy. If the only force which acted on them previously was the Galaxy's gravitational attraction, their velocity relative to the galactic centre would be about 380 km/sec. If we further assume, for lack of better information, that the *average* direction of the stream relative to the local standard of rest is given by the centre of the region where the high-velocity clouds are mainly concentrated ($l = 120°$, $b = +40°$, see Section 1), we find that the original velocity relative to the local standard of rest is about 500 km/sec. Because the present space velocity of the observed high-velocity clouds is about 150 km/sec, we consider that roughly 70% of the gas contained in them would be swept-up galactic gas.

I must mention that Puppi, Setti and Woltjer (see Paper 47 in this volume) have recently suggested that the clouds would have been partly braked by the pressure of galactic cosmic rays. In that case the velocity with which the clouds enter the galactic

gas would be lower, perhaps 400 km/sec. But it would still seem probable that something like half of the observed high-velocity gas would be galactic.

We shall consider separately *two hypotheses concerning the distances* of the observed high-velocity clouds:

(*a*) the 'galactic-layer hypothesis', in which they are assumed to lie between 500 and 1000 pc distance (or between 320 and 640 pc from the galactic plane, i.e. in the outskirts of the galactic gas layer);

(*b*) the 'corona hypothesis', where they are assumed to lie between 1000 and 3000 pc distance (between 600 and 2000 pc from the plane).

On hypothesis (*a*) the flow of high-velocity clouds in the direction of the stream would be 4×10^{18} hydrogen atoms per cm^2 per million years, while on hypothesis (*b*) it would be $1{\cdot}0 \times 10^{18}$ in the same units. The original stream, before deceleration by galactic gas, would have a flow of about 3/10 of these amounts, if we omit the effect of cosmic rays.

Is so strong a current coming from intergalactic space plausible? In order to estimate the *intergalactic density required* to keep up such a flow we must take account of the fact that, owing to the attraction by the Galaxy, the flow at 10 kpc from its centre will be considerably stronger than that at a very large distance. The 'accretion' factor involved is about 20 if we consider only the gravitational effect. If there is considerable deceleration by cosmic rays, it will be less by a factor which we estimate to be between 2 and 3. Taking account of the inflow from the southern galactic hemisphere, and allowing for the fact that there should presumably be alternating periods in which matter is expelled from the galactic disk instead of flowing into it, we arrive at the estimates given in Table 1 for the original density at distances between 0·5 and 1·0 Mpc.

Table 1

Intergalactic gas density required for flow of high-velocity gas

Braking by cosmic rays?	Place of deceleration	Original density (10^{-29} g cm^{-3})
no	galactic layer	28
no	corona	7
yes	galactic layer	112
yes	corona	28

All of these values are considerably higher than the 'critical' average density in the expanding universe, which is about 1×10^{-29} g cm^{-3}. But in view of the enormous irregularity of the distribution of matter in the universe, and in view of the circumstance that our Galaxy is part of the Local Group of galaxies, and probably also of the much larger region of excess density surrounding the Virgo Cluster, a higher-than-average density is quite possible. A density of more than 10×10^{-29} g cm^{-3} can, however, probably be ruled out on the basis of the negative outcome of attempts to measure the 21-cm emission from intergalactic gas.

4. EFFECTS ON GALACTIC DYNAMICS

We shall now consider the effects of the flow on the Galaxy. Let us look first at the behaviour of the gas with lower velocity. As we have seen in Section 1, there is, at least down to 20 km/sec, and probably to even lower velocities, a very large preponderance

of negative velocities. These negative velocities are distributed in longitude in a way which appears similar to that of the high velocities, and they show the same outspoken asymmetry between the northern and southern galactic hemispheres. On our present hypothesis the smaller size of the velocities must be due to further deceleration, apparently by sweeping up more galactic gas, for they have a considerably greater average surface brightness.

It takes roughly ten million years to decelerate such clouds as we are observing from a velocity of -150 to one of -30 km/sec. We infer that the present stream must have been going on for at least ten million years, and has therefore, before its deceleration, extended over at least 4 kpc in the direction of its motion. These data would again seem to suggest that we are witnessing a more or less continuous stream.

On the 'corona' hypothesis, and without braking by cosmic rays, the average flow of intergalactic matter into the Galaxy would be $0{\cdot}2 \times 10^{18}$ hydrogen atoms per cm^2 per million years. The flow into 1 cm^2 of the galactic layer is then $0{\cdot}13 \times 10^{18}$ atoms per million years. According to Van Woerden's unpublished estimate, the average number of hydrogen atoms in a column of 1 cm^2 perpendicular to the layer is 7×10^{20}. If we add 25% (by mass) of helium, and neglect molecular hydrogen, we find that the layer would double its mass in 5×10^9 years. If the incoming stream carries no angular momentum, the angular momentum per unit mass would be halved in the same period. This appears rather excessive. It would seem that we either have to assume that the average flow over a long period of time is markedly less than what we observe at present, or that the existing layer contains a considerable proportion of molecular hydrogen. All this would become much worse if we assumed that the high-velocity clouds have been braked in the galactic layer instead of in the corona. From these considerations it is likely that there exists a gaseous corona extending to several kpc from the galactic plane, with an average density of the order of $1{\cdot}0 \times 10^{-3}$ atoms per cm^3.

As we have seen, the flow at moderate velocities is considerably stronger, perhaps a factor of 5 at -30 km/sec. This would double the amount of gas below the average height of these moderate-velocity clouds in a time of the order 10^9 years. Most of this inflow is probably balanced by *outflow* in other regions of the disk. But it is clear that an exchange of gas on this scale between different parts of the disk must have a large effect on the dynamics of the gas in the disk. Such effects have been provisionally considered in the article mentioned (Oort 1966). They involve circulation of gas over large distances.

5. CLOUD STRUCTURE OF THE HIGH-VELOCITY GAS

In Section 1 I have mentioned the cloudy structure of the high-velocity gas. Some of these 'clouds' have been studied in rather great detail by Hulsbosch and Raimond (1966). Figures 1, 2 and 3 illustrate some properties of their 'Object A'. This object, with a radial velocity of -175 km/sec, has an exceptionally large central surface density, of 16×10^{19} atoms per cm^2, an equivalent diameter of $3\overset{\circ}{.}5$, or 60 r pc, and a total mass of 2500 r^2 solar masses, if r is the distance in kpc. It is possible that this object has come from intergalactic space as a very condensed cloud, and that it has acquired its large internal velocity dispersion (11 km/sec in the radial component) quite recently. There are several more objects of the same nature, though smaller in mass. In addition, a number of features has been found which extend over angles of 10° to 20°, but must nevertheless be considered as connected structures, because the velocity is almost

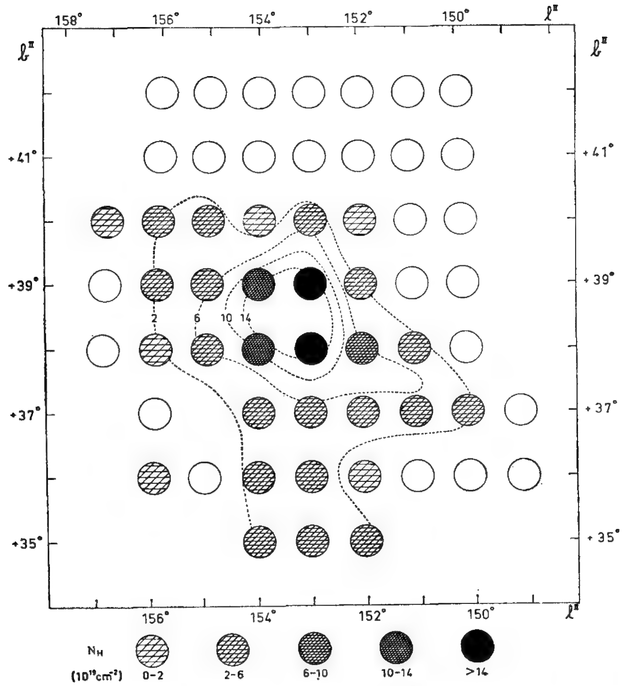

FIG. 1. Object A. The circles showing the positions at which observations have been made have diameters of 0°.5, somewhat smaller than the beamwidth (0°.6) of the Dwingeloo radio telescope at 21 cm. Different hatchings indicate the number of atoms in the line of sight in a column of 1 cm² cross-section. Open circles mark positions where observations failed to show radiation at the velocities of Object A. (Hulsbosch and Raimond 1966)

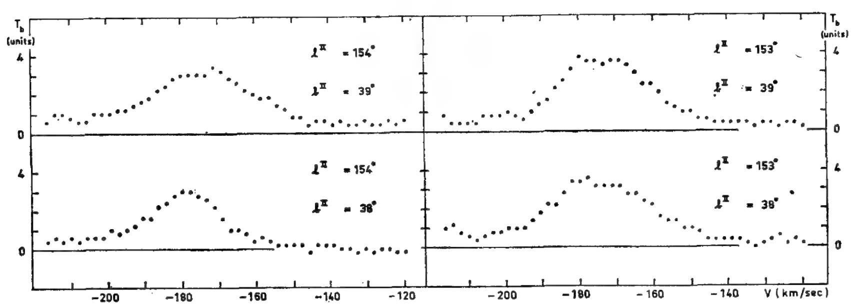

FIG. 2. Velocity profiles in the central region of Object A. Except for the lower left one, the profiles seem to consist of more than one component. The bandwidth used for these profiles was 20 kHz = 4·2 km/sec. The units of brightness temperature (T_b) are approximately equal to degrees Kelvin. (Hulsbosch and Raimond 1966)

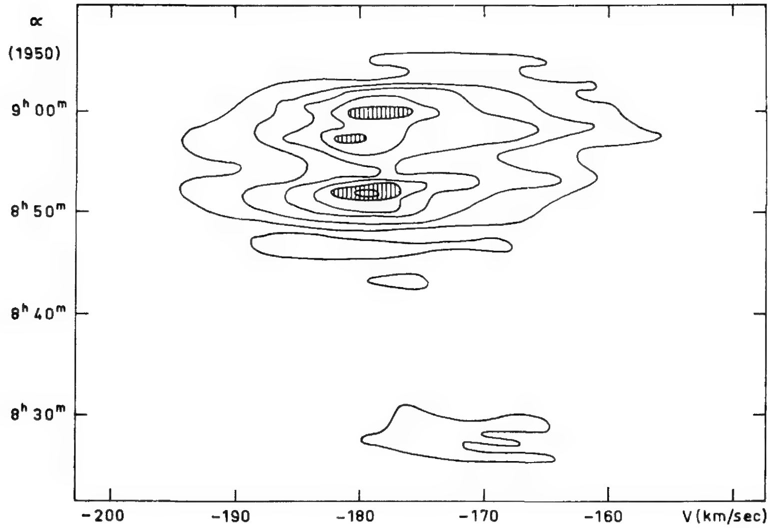

FIG. 3. Distribution of density and velocity in a section through Object A at declination + 62° 20′, showing two concentrations in the space distribution. Maximum brightness temperature is about 6 °K. (From observations by G. W. Rougoor, made with the 300-foot (91-m) reflector at Green Bank.)

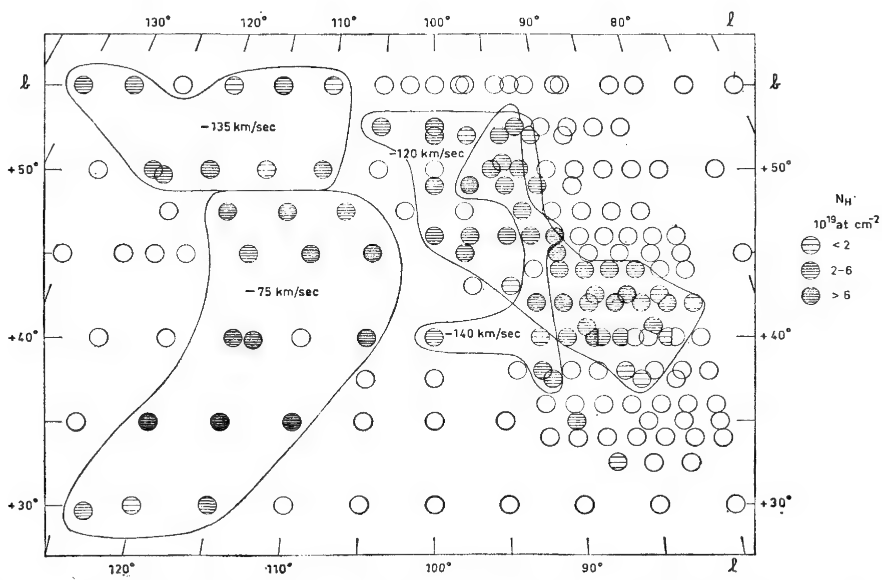

FIG. 4. Surface densities in the complex of high-velocity clouds between $l = 80°$ and 130°, $b = +30°$ and $+55°$. Open circles denote positions where an observation was made but no high-velocity gas was found. The diameters of the circles correspond to 1·6 times the beamwidth of the Dwingeloo telescope. (Hulsbosch, unpublished)

constant over their entire surface. Four of these are shown in Figure 4, and the detailed structure of one of them in Figure 5. They might possibly be clouds that are analogous to 'Object A', but seen in a later, more expanded, stage. A difficulty in the way of such an interpretation is that they must then have moved undisturbed by other interstellar matter during the whole time of this expansion.

It may be that the bulk of the gas in intergalactic space consists of small and rather condensed clouds.

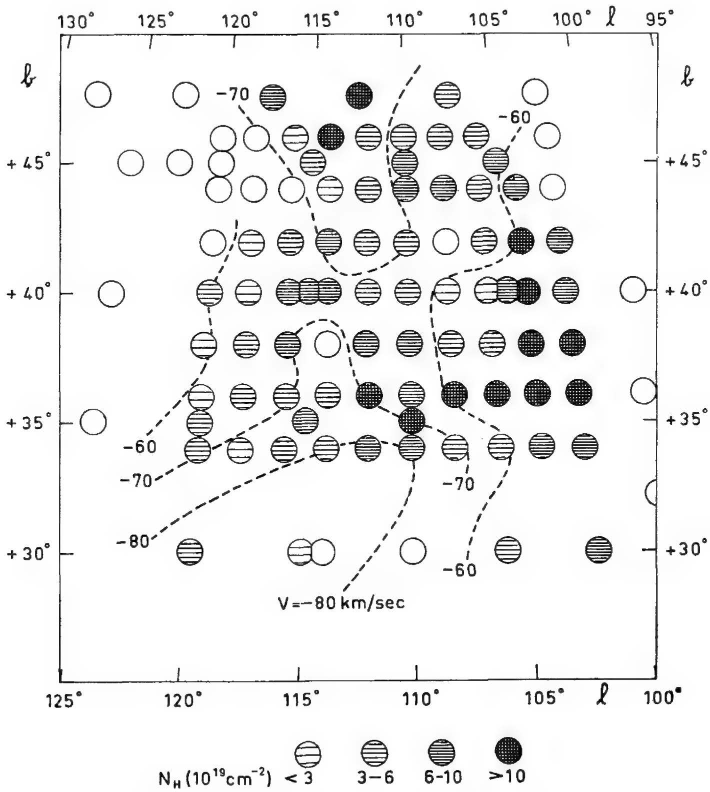

FIG. 5. Detailed observations of the feature marked − 75 km/sec in Figure 4. (Hulsbosch, unpublished)

6. CONCLUDING REMARKS

There are still many problems to be solved before the proposed hypothesis for the origin of high-velocity clouds can be definitely accepted. Two crucial problems are the following. (1) How can the matter in the shock front preceding the cloud which collides at a high velocity with the interstellar gas, be cooled fast enough to make it possible for the hydrogen atoms to recombine? (2) How can the small intergalactic clouds have originated and lived during the lifetime of the Universe? The first problem is being studied by Savedoff *et al.* (1967; see also Paper 49).

Finally, there remains the problem of the high average density required in the region of the Local Group. In this connection we wish to refer to the interesting suggestion made by Šklovskij (Paper 48 in this volume), according to which the 21-cm radiation from these high-velocity streams might have been enhanced by maser action. In such a case the real densities would be lower than those estimated above on the supposition of collisional excitation.

REFERENCES

Habing, H. J. 1966, *Bull. astr. Inst. Netherl.*, **18**, 323.
Hulsbosch, A. N. M., Raimond, E. 1966, *Bull. astr. Inst. Netherl.*, **18**, 413.
Münch, G., Zirin, H. 1961, *Astrophys. J.*, **133**, 11.
Oort, J. H. 1966, *Bull. astr. Inst. Netherl.*, **18**, 421.
Savedoff, M. P., Hovenier, J. W., Van Leer, B. 1967, *Bull. astr. Inst. Netherl.*, **19**, 107.

47. INFALLING METAGALACTIC GAS CLOUDS AND GALACTIC COSMIC RAYS

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We wish to suggest (see also Puppi, Setti and Woltjer 1966) that the interaction between matter falling into the Galaxy and cosmic rays may be important both in slowing down the infalling material and in contributing to the acceleration of cosmic rays. This suggestion is based on the following observations:

1. The rate at which an infalling gas stream of 1 solar mass ($\odot$) per year must dissipate its potential energy is comparable to the energy requirement for cosmic-ray acceleration.

2. If gas with some magnetic field falls into the Galaxy with typical velocities of 100 km/sec, a typical cosmic-ray particle confined by these fields will double its energy in a time of the order of 10^8 years, which is about the median lifetime of cosmic rays in the Galaxy.

3. Inspection of the equation of motion for a uniform inflow of 1 $\odot$/year shows that it would experience strong deceleration down to about 10 kpc from the galactic centre. The uniform distribution of decelerated gas would be Rayleigh-Taylor unstable and thus tend to break up into more discrete features.

We have not yet made a proper self-consistent dynamical model, in which the hydrodynamic equations for the gas and the diffusion equations for the cosmic rays should be solved simultaneously. Thus our discussion is still provisional.

REFERENCE

Puppi, G., Setti, G., Woltjer, L. 1966, *Nuovo Cim.*, **45**, 252.

I.A.U. Symposium no. 31, 1967

48. MASER EFFECTS IN THE INTERSTELLAR HYDROGEN CLOUDS OF THE GALACTIC HALO

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ABSTRACT

It is suggested that the neutral hydrogen atoms in clouds with high negative velocities observed at high galactic latitudes may, when moving towards a galactic H II region, be excited by radiation in the red wing of the Lyman-α profile. The steepness of this wing may cause a population inversion of the hyperfine-structure levels. Consequently, estimates of the hydrogen density in the high-velocity clouds, and of the flow of matter towards the galactic plane (or into the Galaxy), when based on the assumption of collisional excitation, may be too high by two orders of magnitude.

Analysis of the difficult problems described by Oort (Paper 46) makes it desirable, in my opinion, to consider a new approach. This approach is based on the fact that in some regions of the halo the conditions of excitation of hyperfine-structure levels of hydrogen must be strongly different from those inside the relatively dense neutral-hydrogen zones in spiral arms. Instead of the excitation by means of collisions between hydrogen atoms, which operates in H I regions, scattering of $L\alpha$ radiation can be of decisive importance in these halo regions. In some circumstances this mechanism of excitation can lead to a population inversion on the upper level of the hyperfine structure of the ground state of hydrogen.

Recently, this problem was explicitly discussed by Varšalovič (1966), who has shown that inversion can arise in the following two cases.

(1) When hydrogen atoms occur in a directed beam of Lyman-α quanta, their spins are oriented along the axis of the beam, so that the population of the magnetic sub-levels changes. The calculation by Varšalovič shows that $N_{1,0}/N_{0,0} = 0{\cdot}987$; $N_{1,+1}/N_{1,0} = 1{\cdot}013$. This is equivalent to an inversion with the spin temperature $T_{s+1} = -5{\cdot}2$ °K.

(2) The inversion may also occur if the intensity distribution of $L\alpha$ radiation (whether isotropic or not) is strongly dependent on the frequency. As one can show, under some conditions in the case considered, $N_{1,m}/N_{0,0} \sim I(\nu + \Delta\nu_0)/I(\nu)$, where $\Delta\nu_0 = 1{\cdot}42 \times 10^9$ Hz, the frequency of the 21-cm line, and the inversion can be large enough.

It is clear that, for clouds in the disk, case (1) is unrealistic owing to isotropy of $L\alpha$ radiation. Moreover, $L\alpha$ quanta will be absorbed in H I regions, so their final number is very small. In the halo, however, this mechanism will give some inversion of population.

Case (2) is a more interesting one; it corresponds to the process of excitation of hydrogen atoms by the red wing of the $L\alpha$ line, when an interstellar cloud moves towards the source of the radiation.

In the galactic disk the average relative velocity of gas clouds and $L\alpha$ sources (hot stars) is small, and, moreover, the density of $L\alpha$ quanta is very small; so this mechanism of excitation can hardly be effective. But in the galactic halo the situation can be different.

Let us imagine a large H II region, situated close to the border of a spiral arm. In this case, the $L\alpha$ quanta from the H II region will diffuse right into the galactic halo. While the H II region takes part in the rotation of the Galaxy, the velocity of galactic rotation for the interstellar clouds in the halo may be smaller by about 100 km/sec. But the peculiar velocities of halo clouds may also be about 100 km/sec. So, if the direction of the peculiar motion coincides with that of differential galactic rotation, no effect of inversion by the second mechanism will occur. It is only in the case of relative approach between an H I cloud in the halo and an $L\alpha$ source that the maser effect may be expected to operate.

It is known that most of the $L\alpha$ quanta escaping from an H II region are displaced to either side of the central frequency of the line, by about $3\Delta\nu_D$, where $\Delta\nu_D \approx 1 \times 10^{11}$ Hz is the Doppler half-width corresponding to the characteristic temperature of H II regions (10^4 °K). So, the profile of the $L\alpha$ line has two maxima, separated by $6\Delta\nu_D$. In the interval $|\Delta\nu| > 3\Delta\nu_D$ the intensity of the line drops according to a Gaussian law: exp $(\Delta\nu/\Delta\nu_D)^2$. In the red wing a frequency displacement of $\Delta\nu_0 = 1{\cdot}42 \times 10^9$ Hz actually causes a 10% variation of intensity. Thus, under favourable conditions, $N_{1,m}/N_{0,0} = 1 + \Delta \approx 1{\cdot}1$, and the inversion will be sufficiently large.

Let us suppose now that in the galactic halo there are many clouds, with random motions whose velocity dispersion is about 100 km/sec, and with hydrogen concentrations of about 10^{-2} to 10^{-3} cm^{-3}. These clouds do not screen each other, and the intercloud space is transparent enough for $L\alpha$ quanta. The last supposition is a quite natural one, because the density of gas between the clouds may be several tens of times less than that in the clouds. At the same time, the ionization of the hydrogen is large enough.

Every cloud with a high negative velocity relative to a source of $L\alpha$ quanta will scatter these quanta mostly in the far violet wing of its absorption coefficient. This is due to the exponential increase of the intensity towards the violet; at the same time, the scattering coefficient in the far wing of the profile decreases slowly: $k_\nu \sim (\Delta\nu)^{-2}$. The effective cross-section for $L\alpha$ in the far wing is roughly 10^{-17} to 10^{-18} cm^2, and the linear dimension of the cloud is about 10^{20} cm. Since the density $n_H = 10^{-2}$ to 10^{-3} cm^{-3}, the optical thickness of every cloud for those 'displaced' $L\alpha$ quanta does not exceed a few units; it is most probable that this optical thickness is less than unity. Therefore, the $L\alpha$ profile will not be changed much in the cloud.

The final conclusion is: if the population of hyperfine-structure levels is determined by scattering of $L\alpha$ photons, inversion may occur.

According to a very rough estimate, at least in some halo clouds, the population of hyperfine-structure levels is regulated not by inelastic collisions but predominantly by $L\alpha$.

If the $L\alpha$ scattering creates a population inversion in a cloud, the amplification of the maser can be determined by:

$$\tau(\nu) = \frac{1}{8\pi}\frac{\lambda^2}{\Delta\nu} A_{mn}\frac{g_m}{g_n} n_n \left(1 - \frac{g_n}{g_m}\frac{n_m}{n_n}\right) l. \tag{1}$$

Now we have:

$$\frac{n_m}{n_n} = \frac{n_{1,0} + n_{1,1} + n_{1,-1}}{n_{0,0}} = 3(1 + \Delta),$$
$$1 - \frac{g_n}{g_m}\frac{n_m}{n_n} = -\Delta. \tag{2}$$

Substituting (2) into (1) we get:

$$\tau(\nu) = -\frac{3}{8\pi}\,\frac{\lambda^2}{\Delta\nu}\,n_n A_{mn} l \triangle \approx -\frac{3}{32\pi}\,\frac{1}{\Delta\nu}\,\lambda^2 A_{mn} n_{\mathrm{H}} l \triangle, \tag{3}$$

where $n_{\mathrm{H}} = n_n + n_m \approx 4n_n$. Taking now $l \sim 100$ pc $= 3 \times 10^{20}$ cm, $\Delta\nu \sim 5 \times 10^4$ Hz, $A_{mn} = 2{\cdot}85 \times 10^{-15}\,\mathrm{sec}^{-1}$, $\triangle \sim 0{\cdot}1$, $n_{\mathrm{H}} \sim 3 \times 10^{-3}\,\mathrm{cm}^{-3}$, we get for a 'standard' halo cloud $\tau \sim 0{\cdot}1$, and the amplification is large enough. Such a cloud would continuously operate as an isotropic maser of travelling-wave type.

Our Universe is filled by relic black-body radiation with a temperature of about 3 °K. The 21-cm quanta of this radiation would, when passing through the cloud, be amplified several times. To reach a similar surface brightness by a thermal mechanism (i.e., by means of collisions), the density of the cloud would have to be several hundred times higher. Consequently, if we consider such a cloud by common methods, we may overestimate the gas density by a factor of several hundred.

We suggest that part of the clouds observed at high latitudes may be described by the maser mechanism. This new interpretation is in accord with the basic fact that the majority of the measured radial velocities of these clouds are negative. In such clouds the excitation of the hydrogen atoms can be caused by the red wing of $L\alpha$.

It seems to me that these clouds are local objects, and that their distances from the Sun are moderate and hardly exceed 1 kpc. Local inhomogeneities may explain the asymmetry of the distribution of these clouds in galactic longitude.

If this interpretation is correct, then the mass of the interstellar halo gas falling into the galactic plane should be reduced by about two orders of magnitude according to the proposed interpretation; thus the influx will be (1 to 3) $\times\ 10^4\,M_\odot$ per 10^6 years. The gas located far from the galactic plane may be naturally explained by the loss of matter from older stars of the spherical population of the Galaxy. According to Oort (1966), this loss of mass by the spherical population is about $4 \times 10^4\,M_\odot$ per 10^6 years.

REFERENCES

Oort, J. H. 1966, *Bull. astr. Inst. Netherl.*, **18**, 421.

Varšalovič, D. 1966, *Zu. eksp. teor. Fiz.* (in press).

I.A.U. Symposium no. 31, 1967

49. HIGH-VELOCITY CLOUD COLLISIONS

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At the suggestion of Professor Oort, we have investigated a model for the collision of a high-velocity cloud with galactic gas. Oort considers a snow plow model, for the incoming cloud has a unique density and velocity, etc., and conservation of momentum is used as for such a solid body. The three-dimensional hydro-dynamic problem is quite expensive to carry out both in computer and in human time. We consider alternatively a shock-tube model which permits easy comparison with observations.

Consider a flow of extragalactic matter at velocity V_C, density ρ_C, and temperature T_C, into the Galaxy which has V_G, ρ_G, T_G respectively. We see this (Figure 1) at a time t later, when a portion (shaded in the figure) has cooled and recombined.

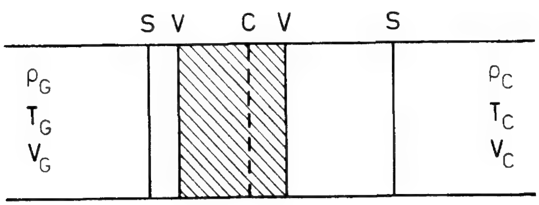

FIG. 1. Collision of an extragalactic cloud (density ρ_C, temperature T_C, velocity V_C) with galactic gas (ρ_G, T_G, V_G). S = shock fronts, C = contact surface, V = recombination fronts.

Actually, we need consider only two parameters: the collision velocity $|V_G - V_C|$, which is of the order of the escape velocity with respect to the local standard of rest, and the ratio ρ_G/ρ_C. The initial temperatures of 10^4 °K or less are negligible compared to $(V_G - V_C)^2$, and, since our observations are in terms of surface densities, which are proportional to $\rho_G |V_G - V_C| t$, no knowledge of the absolute value of ρ_G is required, as cooling times are inversely proportional to densities.

As an example, if $|V_G - V_C| \approx 500$ km/sec as suggested by Oort (1966), $v = 127$ km/sec (which symbolizes the observed velocities) corresponds to the case $\rho_G/\rho_C = 9$, and yields a surface density of about 10^{19} neutral hydrogen atoms per cm^2. For further information, we refer to our forthcoming paper (Savedoff, Hovenier and Van Leer 1967).

REFERENCES

Oort, J. H. 1966, *Bull. astr. Inst. Netherl.*, **18**, 421.
Savedoff, M. P., Hovenier, J. W., Van Leer, B. 1967, *Bull. astr. Inst. Netherl.*, **19**, 107.

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50. DISCUSSION ON HIGH-VELOCITY GAS

T. K. Menon: In a recent survey of the *region around the Cygnus Loop*, I have found two high-velocity clouds in the region, one at about -40 km/sec and the other at about -70 km/sec. These clouds appear to correlate with the optical features in the region. Because of these results, one should not dismiss the supernova origin of the high-velocity clouds. The regions surrounding other supernova remnants should be similarly studied.

F. J. Kerr: In all the suggested interpretations, it has been assumed that the high-velocity clouds are falling in towards the Sun. We should remember, however, that only one component of the motion has been measured, and we do not know the total space motion.

In the part of the sky where the main group of high-velocity clouds has been observed, galactic rotation can give rise to fairly large negative values of radial velocity. Also we know that on this side the outer part of the galactic disk bends upwards towards positive galactic latitudes. There is thus a preference, in this part of the Galaxy, for distant material to appear at negative velocities and positive latitudes, without the need to invoke a special mechanism.

I would suggest that the high-velocity clouds are *loosely-bound satellites of the Galaxy*, at considerable distances from the Sun. On this picture, the main group of these clouds forms a far extension of the tilted edge of the galactic disk, well beyond the feature studied by Habing (1966), which may be a far outer arm. The group would then be a highly-fragmented 'anti-Magellanic Cloud'. It is interesting that the figure obtained for the total mass of the high-velocity gas by putting a distance of 50 kpc into Blaauw's formula (Section 4 of Paper 45) is $15 \times 10^6 M_{\odot}$, which is just one order of magnitude less than the hydrogen mass in either of the Magellanic Clouds. High-velocity clouds away from the main group could similarly be in the far outskirts of the Galaxy, moving in circular or elliptical orbits.

J. H. Oort answers: I have considered the possibility that the high-velocity objects would be things like the Magellanic Clouds. A serious objection is, however, the observation of some intermediate-velocity clouds by Münch and Zirin (1961); these clouds at least must be at less than about 1 kpc distance, and the similarity between the phenomena observed at intermediate velocities and those at high velocities suggests a common interpretation.

A. Blaauw: Šklovskij's suggestion of a *maser effect* (Paper 48) raises the question of the origin of the exciting radiation. In this connection it is of some interest to point out the coincidence of the mean longitude of the high-velocity clouds with that of the *h and* χ *Persei Association* ($l \approx 135°$). This is by far the richest concentration of supergiants within several kiloparsecs from the Sun. At an earlier stage (between 10^6 and 10^7 years ago) it must have given rise to an exceedingly large or intense H II region. At present the area is remarkably void of interstellar matter, and the energetic radiation must escape from it relatively easy. In relating this source with the high-velocity clouds, on the basis of

Šklovskij's mechanism, one must take into consideration the time-lag between the moment of emission of the exciting radiation by the H II region and that of the induced 21-cm emission by the clouds.

H. L. Helfer adds: There are also several strong OB associations beneath the galactic plane, in the direction of the Cygnus Arm. These extend to about 10° below the plane, and there has been no report* of high-velocity clouds from this direction.

B. J. Bok: If the Šklovskij-Varšalovič maser effects exist, they should be observable in the vicinity of the *Large Magellanic Cloud*, where we have a large supply of relatively unobscured OB supergiants rich in ultra-violet radiation.

J. H. Oort: The suggestion by Šklovskij is extremely interesting and may well be of great importance for the interpretation of the high-velocity clouds. I see two principal difficulties. In the first place there is the fact that the *intermediate-velocity clouds* observed by Münch and Zirin (1961) show an approximately normal 21-cm emission for clouds with Ca II lines of the observed strength. So in this case there appears to be no great stimulation by maser action.

Another difficulty is again the relation between the phenomena at intermediate and at high velocities. The smaller-velocity clouds are likely to show weaker maser effects, and we should thus expect them to give less intense 21-cm radiation. The opposite is the case, however.

G. L. Verschuur comments: Oort alludes to the importance of the association of a few Münch-Zirin features with the 21-cm high-velocity features. We have heard earlier in this Symposium (Papers 1, Van Woerden, and 2, Goldstein, plus pertinent discussion) about the difficulty of associating optical absorption lines with the relatively wide 21-cm emission features observed at low galactic latitudes. These high-velocity features are even wider; therefore, how certain can we be that this correlation is real?

Oort answers: At the high galactic latitudes and fairly high velocities concerned, the identification between optical absorption lines and 21-cm emission is very much easier. In my opinion the correspondence is well established. Moreover, the really important thing is that these intermediate-velocity absorption features *exist*, and that the statistics by Münch and Zirin give an indication that they lie at large distances from the galactic plane.

J. E. Baldwin asks: Have attempts been made to observe *21-cm absorption* in the continuum spectrum of extragalactic sources through these high-velocity clouds?

If the temperatures in the clouds are high, so that the optical depths are very small, then attempts should be made to study the Faraday-rotation measures of extragalactic sources in these directions.

Oort answers: No attempts to observe 21-cm absorption have been made, so far as I know. But the surface density of the clouds is so low that it is doubtful whether the absorption would be observable; particularly since the temperature of these clouds, as indicated by their very wide profiles, may be much higher than the average temperature of clouds in the galactic plane, so that the absorption coefficient may be expected to be

*The Cygnus Loop, in whose surroundings Menon has found hydrogen with moderately high velocities (see earlier in this Discussion), lies in the region indicated by Helfer.—*Editor.*

rather lower. It would, however, be extremely interesting to try to measure the absorptions and thereby determine the temperature.

V. L. Ginzburg: If in a cloud of neutral hydrogen the population of levels is inverted, *continuous radiation* of 21 cm wavelength will not be absorbed but *enhanced*. Therefore, if we see a cloud projected on some bright detail on the sky, this cloud will be brighter than it would be without the detail. This may help to prove Šklovskij's hypothesis. I wish to mention, however, that this hypothesis of population inversion of the hyperfine-structure levels in hydrogen clouds seems to me not very plausible. In particular, in this connection one should explain why there are no clouds with $|\tau| \gg 1$. Such clouds would have to be bright, but nothing of the kind is observed.

B. F. Burke: K. C. Turner and I—and independently also Woltjer, I believe—applied the virial theorem to the cloud of -175 km/sec velocity, assuming equilibrium. There are enough observables to obtain *mass and distance*, although the equilibrium assumption is a doubtful one. The resulting mass is $10^8 M_\odot$, at a distance of several hundred kiloparsecs.

D. W. Sciama: I should like to comment on Oort's second crucial point (see Section 6 of Paper 46), namely, the origin and preservation of hydrogen clouds in intergalactic space and the *density of the intergalactic medium*. It is important to distinguish between ionized and neutral hydrogen in intergalactic space. The following limits can be placed on the density of the neutral hydrogen:

(*a*) if the red-shifts of quasars are cosmological in origin:

$$\rho_H \leqslant 10^{-36}\ \mathrm{g\ cm^{-3}}, \qquad (1)$$

from the lack of any absorption edge at the red-shifted Lyman-α wavelength, a method proposed by Scheuer and by Gunn and Peterson (1965);

(*b*) if not, then

$$\rho_H \leqslant 10^{-29}\ \mathrm{g\ cm^{-3}}, \qquad (2)$$

from the lack of 21-cm emission.

By comparison, the density of the Universe, if it can just expand indefinitely in the absence of a cosmical constant, is given by

$$\rho \sim 2 \times 10^{-29}\ \mathrm{g\ cm^{-3}}. \qquad (3)$$

If (1) applies, the gas must be highly ionized, which requires a kinetic temperature T of the order of $0{\cdot}5 \times 10^6$ °K.

In a cluster like our own Local Group, the density may be considerably higher. Kahn and Woltjer (1959) suggested

$$\rho \sim 2 \times 10^{-28}\ \mathrm{g\ cm^{-3}},\ T \sim 0{\cdot}5 \times 10^6\ ^\circ\mathrm{K}. \qquad (4)$$

The cooling-time for such a gas is of the order of 10^{10} years, and it seems unlikely that it would contain neutral-hydrogen clouds. I therefore suggest that these *clouds form after the process of accretion by the Galaxy has already begun.*

Figure 1 shows the shock wave that may form in the gas which has been perturbed by the Galaxy (as discussed by Ruderman and Spiegel). Behind the shock there is a substantial density increase, and conditions may be suitable for cloud formation by thermal instability, the cooling time now being perhaps only 10^9 years. The clouds then

cool until they become at least partially neutral. Some of their transverse momentum will be lost as they collide with slower (or oppositely) moving gas, somewhat like in the old accretion theories. They can then be captured by the Galaxy. One attractive feature of this mechanism is that it leads to clouds entering the Galaxy from behind, that is, from a direction opposite to that of the motion of the Galaxy relative to the intergalactic gas. This is in accord with the observations as analysed by Oort.

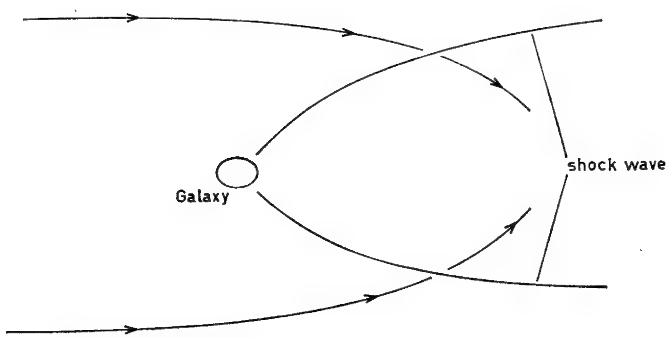

FIG. 1. Shock wave forming in intergalactic gas flowing past the Galaxy.

S. A. Colgate asks Sciama: When calculating the ionization fraction, did you use the Saha theory or rather detailed balance and atomic theory? With the latter, I cannot get the ionization fraction at a temperature corresponding to 50 eV much higher than about 10^{-7}.

Sciama answers: We used the empirical cross-sections, which seemed to be more accurate than the theoretical ones. The radiation turns out to be unimportant.

S. J. Goldstein comments: Recently I have used a multi-channel switched-load receiver to look for 21-cm line emission from a general distribution of *intergalactic neutral hydrogen*. If absorption of background continuum radiation is negligible, the average density of neutral hydrogen atoms is less than $1{\cdot}2 \times 10^{-5}$ atoms/cm^3 ($2{\cdot}0 \times 10^{-29}$ g cm^{-3}) for the region within 12° of the north celestial pole. An earlier attempt (Goldstein 1963) had given an upper limit of $2{\cdot}1 \times 10^{-5}$ atoms/cm^3 = $3{\cdot}5 \times 10^{-29}$ g cm^{-3}.

L. Woltjer remarks: The original reason for Kahn and Woltjer (1959) to propose the *dense intergalactic medium* which Sciama discussed above was the difficulty of making our Galaxy and the Andromeda Nebula a bound double-galaxy. The new parameters for the rotation of the Galaxy and for the distance from the Sun to the centre, plus the new mass of our Galaxy, all seem to have weakened our original arguments greatly. Therefore, the original motivation for this medium has largely disappeared, although it still may come in handy in a number of ways, but that is a different question.

Sciama asks Woltjer: Does this mean that you abandon your explanation of the *tilt in the galactic disk* as being due to an intergalactic wind?

Woltjer answers: Since our paper appeared in 1959, the mass of the Magellanic Clouds has been revised upwards by a factor of ten. This makes an interpretation of the bending

of the gas layer in terms of the gravitational effects of the Clouds more likely.* It remains, of course, true that an intergalactic wind could significantly perturb the gaseous component of a galaxy.

G. R. Burbidge: If one supposes that the infalling gas clouds originate from intergalactic material (cf. Oort, Paper 46), then one is forced to conclude that the density of the 'local' intergalactic medium is very high – perhaps unreasonably so. Moreover the original intergalactic clouds must be rather small and dense, and their long-term stability is difficult to understand. In view of these difficulties I think that one should look into alternative ideas. The suggestion that the clouds have resulted from an *explosion in the galactic-centre region* still is very attractive to me. I agree that it also leads to severe problems, but it is not clear at the moment whether the difficulties are worse than they are in the case of the intergalactic hypothesis.

D. Lynden-Bell: Very violent *tidal effects* are observed even in the optical parts of some galaxies, e.g. NGC3187 and 3190 in Leo, in which the outer part of a spiral seems to have been bent at right angles to its principal plane. One would expect still more violent effects in the more extended radio-emitting parts of spirals.

When material bent right out of the plane returns to its galaxy after the encounter, it must form phenomena similar to those observed in the high-velocity clouds.

S. B. Pikel'ner: There are some troubles about the origin of high-velocity hydrogen clouds in intergalactic space. Moreover, if there are many such clouds, there should be absorption and emission, which are not observed. Therefore, this hypothesis is open to question. Another possibility to be considered is the following. *Our Galaxy may have a bridge and a tail*, as have interacting galaxies. The gas of this tail should fall into the Galaxy from definite regions of the sky.

M. S. Roberts: In this connection, may I point out that there is a pair of galaxies, with a 21-cm bridge in between, in our direct neighbourhood.

S. I. Syrovatskij: I should like to mention the possible role of *cosmic-ray pressure* in the generation of the neutral-hydrogen flows discussed by Blaauw and Oort.

We know that there must be a strong pressure gradient of cosmic rays between the galactic disk and intergalactic space, where we anticipate a much lower cosmic-ray density. This gradient may be compensated only by the gravity of gas above the disk; the gas interacts with the cosmic rays by means of the magnetic field. But such an equilibrium is unstable, as has been shown in earlier papers by Pikel'ner and more recently by E. N. Parker. The cosmic rays stretch the field lines in some places out of the Galaxy, and in some other places gas falls down to the disk. With the steady generation of cosmic rays in the disk, a circulation of the gas above the galactic plane must have been established.

It is remarkable that, if we use as crude estimates for the number of hydrogen atoms in a unit column 5×10^{19} cm^{-2}, for the mean flow velocity 100 km/sec, and for the characteristic height a figure of the same order as the disk radius, namely 15 kpc, we obtain a mean concentration $n_{\mathrm{H}} = 10^{-3}$ cm^{-3}, and a time of ascent of about 2×10^8 years, which is of the same order as the time of recombination of hydrogen at a temperature of 10^4 °K. Thus, under such conditions, the ionized hydrogen pushed away from the

*Cf. the remarks by Habing in the discussion following Paper 24.—*Editor.*

galactic disk by cosmic rays may in large part recombine and flow down as streams formed by the instabilities mentioned above. The time of about 2×10^8 years is the same as the life-time of cosmic rays in the Galaxy estimated from other data. The power of cosmic rays needed for generation of such motions does not exceed some tens of percent of this power of cosmic-ray sources in the Galaxy, according to our estimate. In this connection a study of the correlation between hydrogen streams and magnetic-field structure at high latitudes would be of great interest.

M. P. Savedoff: Without having tables of recombination coefficients or energy rates with me, I am worried about the fact that, if the cosmic-ray intensity up there is high enough, the energy received by the gas from the cosmic rays may be so high that the gas is too hot to recombine. Normally, the energy radiated by the gas is proportional to the density squared; if the cosmic rays are as intense there as they are down here, they supply an extra factor of a thousand relatively on the energy input.

Oort: Syrovatskij suggests that the high-velocity clouds might be streams flowing back to the galactic plane in regions bordering the instabilities in the magnetic field considered by Pikel'ner and by Parker, by which the gas might have been gradually pushed up to large distances from the galactic plane.

An objection is that it seems difficult to explain why they would in this case be coming from specific longitudes.

A more serious difficulty, which I had already pointed out in connection with Field's idea that the high-velocity clouds might have been formed by gravitational instabilities in a hot corona, and of which I was reminded by Woltjer, is that clouds formed in this way could hardly be expected to gain high velocities in falling through the same corona from which they are condensing.

(*Note:* The last three contributions, by Syrovatskij, Savedoff and Oort, were made in the General Discussion concluding Part II of the Symposium.—*Editor.*)

REFERENCES

Goldstein, S. J. 1963, *Astrophys. J.*, **138**, 978.
Gunn, J. E., Peterson, B. A. 1965, *Astrophys. J.*, **142**, 1633.
Habing, H. J. 1966, *Bull. astr. Inst. Netherl.*, **18**, 323.
Kahn, F. D., Woltjer, L. 1959, *Astrophys. J.*, **130**, 705.
Münch, G., Zirin, H. 1961, *Astrophys. J.*, **133**, 11.

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Chapter II G

Spiral Structure of the Galaxy

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'*Then you must do something non-linear, or you must simply publish your results.*'

K. H. Prendergast, in Paper 51

51. THEORIES OF SPIRAL STRUCTURE*

(Introductory Report)

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1. INTRODUCTION: WHAT IS A SPIRAL ARM?

This will be rather an unusual introductory talk: I have no slides, almost no equations, and I will not be talking about my own work. I am supposed to speak about the theories of spiral structure, and I will have to begin by redoing some quite ancient considerations.

Obviously the first thing that has to be decided is: what is a spiral arm? I am not going to attempt to answer this, but I would like to point out that one can split opinions to a certain extent between those people who would like to think of spiral arms as large-scale coherent structures, extending almost from the nucleus to the edge of the Galaxy, and those who would like to think of spiral structure as a combination of many detached features (Figure 1), where the structures that one can really follow do not extend over a considerable fraction of the radius of the Galaxy. For the most part I shall be speaking about people who attempt to explain something by the first picture.

2. THE WINDING PROBLEM

Let us therefore start by assuming that there is some sort of large-scale, coherent spiral structure in the Galaxy. The next question that naturally arises is: *how long does*

*The following text has been composed from a tape-recording. The style of the spoken word has been generally maintained, which for a communication on this subject seemed an advantage rather than a disadvantage. Paper 51 should be read together with Paper 52. The notations in the two papers are unfortunately different: Prendergast's φ, m, s, Ω are equivalent with θ, $-m$, ω and Ω, respectively, in the paper by Lin and Shu.

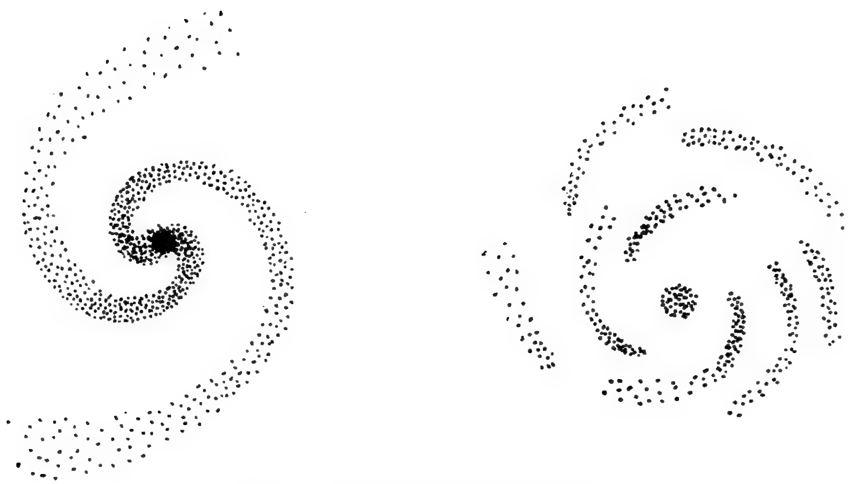

FIG. 1. Models of spiral structure.

it last? If you believe that a spiral arm exists over a very large distance in the Galaxy, you would probably also like to believe that it exists over many rotation periods; whereas, if you think that all you see in most cases is a collection of rather short spiral arms, then you will be quite willing to let these form and dissolve even in a time as short as one rotation period. The reason for introducing the second question of course is the famous winding problem: anything in the Galaxy is sheared at such a rate that at the end of perhaps one or two rotation periods it will be quite unrecognizable.

Under the heading of the winding problem one can say that it takes two different forms. If you believe that a spiral arm is a *thing*, by which I mean that material now in a spiral arm always was in the spiral arm, and that the motions are more or less circular, then you indeed do have a winding problem, and the only way out of it, it would seem to me, is to say that matter is forced along the spiral arm. A number of people have considered this, with various results, but there is not the slightest question but that in most galaxies you would have to find a mechanism for adding a very large amount of angular momentum to the material as it goes out along the spiral arms; or, if you want it to go in, you have to take angular momentum away. That means that you must apply a torque to the material, and you must look for physical factors which can do this. I will not review these, because they all involve things which one otherwise does not like to believe, extraordinarily strong magnetic fields, for example, extending over very large distances.

The other possibility is that a spiral arm is not a thing at all, in the sense that the material now in an arm is always in an arm. If that is not the case then a spiral arm is some sort of a *wave*. Once one says this, of course, one runs into an enormous number of possibilities. A galaxy is a very large tenuous medium, and that allows a gigantic number of different kinds of waves; the sort of waves that you will get depends, among other

things, on what you think the relevant forces are, and whether you are talking mostly about the stars or mostly about the gas, or perhaps about both. I will assume, then, that we are talking about waves, and that we will try to explain long-lasting large-scale coherent features.

At this point we have to split the discussion into *stars and gas*. The case of stars is perhaps physically simpler, because the only thing that affects a star is the gravitational field of a galaxy as a whole, plus some small relaxation effects. If you mention the gas as the predominant constituent of a spiral arm, and as being in fact responsible for the spiral phenomenon, then of course there are many forces that you can quote as being responsible for what you see. There is a possibility, however, which has to be mentioned at this point, and that is the following: that there is a somewhat inconspicuous density wave of the stars, and that the gas reacts very strongly to the presence of small fluctuations in the gravitational field, so that one might say that the gas acts as a tracer of the places where the density of the stars is producing a gravitational sink. With this in mind Professor Lin has been examining the structure of density waves that can exist in disk galaxies, with special emphasis on waves which produce spirals.

You can begin by asking the following thing: how is it that a galaxy consisting of stars has not settled down to a nice, smooth axisymmetric disk? You can answer that by saying: perhaps it has not had time, or you can say: perhaps it has settled down, or tried to, but it found that that situation was unstable. In such a case various sorts of waves could arise which you would attempt, at least at first, to study by a linear analysis.

3. FIRST-ORDER PERTURBATIONS

Let us start from a *zero-order model*, consisting of an axisymmetric, self-gravitating, thin collection of stars. In the first-order model one looks at the first-order perturbations of this system. Now the obvious question that will arise at once is, whether or not all zero-order models are stable. One can get a rather quick view of whether or not they are stable, and if they are unstable, then for what sorts of perturbations. The first question we ask is whether our large, axisymmetric disk of stars is stable against perturbations of a wavelength roughly corresponding to the radius of the galaxy. The answer is: of course, or there would not be a zero-order model to perturb. So we are through with that question; you can be more formal about it if you wish. The second question is: is such a galaxy in general stable against perturbations of wavelengths which are very small? And the answer is: if there is random motion in the galaxy, there is pressure, and of course it is stable; I say again 'of course', because if that were not true, as I disturbed the air in this room by speaking, it would condense into self-gravitating drops and fall to the floor, which it obviously does not do. So it is somewhere between the very largest scale that one can think of and the very smallest one, that one might look for waves that should be either unstable or that can last for a very long time. One may say that the large-wavelength disturbances are stabilized by rotation, and the small wavelengths by pressure. Somewhere in between something interesting may happen. If you would put in a sufficient amount of pressure, that is, sufficiently large random motions of the stars, you might well succeed in stabilizing the entire galaxy.

Let us return to our first-order perturbations on the rotating disk of stars, which we now assume to have a reasonable velocity dispersion, and see what one can do. I will not attempt in any way to reproduce part of C. C. Lin's analysis. Instead I will talk

about a much simpler system. I will treat the stars as if they were a gas with a respectable equation of state. In that case, instead of having the full powers of the Boltzmann equation to deal with, one will have to do only hydrodynamics. And, having made the thin-disk approximation, we have only to look for the motions in the plane; that means two equations of motion and the hydrodynamical equations. I have of course an equation of continuity, and finally I must get the self-gravitational perturbations by examining the Poisson equation. If you write down and linearize these equations of state, it appears that you can perform the following separation of variables. One is looking in this case for normal modes of oscillation of the system, stable or otherwise. That means that one will attempt to factor out everything depending on exp $\{i\, s\, t\}$, where t is the time and s is some characteristic frequency. You have more luck than that: it turns out, upon examining the equations that determine an axisymmetric system, that you can factor out also exp $\{i\, m\, \varphi\}$, where φ is the position angle in the plane of the disk. I am doing nothing more complicated here than a very simple quantum-mechanical problem. This deals with the time-dependence and the angular dependence around the galaxy. We have a wave which has m ridges as one goes around the galaxy, and which rotates with a velocity $-s/m$. This is the *pattern rotation speed.* We are looking for a pattern which, in a suitably rotating frame of reference, does not change. The pattern speed is not necessarily anything like the rotation speed of the galaxy. One is still faced with the remaining variables, for which Lin's device is the following. Remembering that we are looking for waves that are of intermediate wavelength, that is, not so large as the galaxy and not so small as to be squashed, we attempt to make an approximation which is based on essentially the ratio of the wavelength to the diameter of the galaxy, or, as it will turn out, on what is essentially the root-mean-square of the random velocity divided by the speed of rotation at some typical point. This is a small parameter (typically, for our Galaxy, we will put in something of the order of a tenth), and it makes the analysis quite simple, up to a point. Because at this point we are looking for waves with short wavelengths, in a medium which does not change much over a wavelength, that means one will try some variation of the WKB method. That means that we will put in here exp $\{ik\tilde{\omega}/\epsilon\}$; ϵ is a constant of the order of $1/10$.

What I have to talk about then is the behaviour of k, which is the *radial wavelength of the pattern.* The first thing that comes out is that you can determine k at once. Put it into the equation, and you will find that, if there is to be any solution at all, the wavelength must be connected with the other quantities that appear, namely with the number of arms that you have and with the rotation speed of the arms. Without writing down another equation I can simply say that you get a dispersion relation which tells you how fast such a wave will travel, provided you known what the eigenvalue s is. And indeed you must not think of k here as a constant; it is very definitely not a constant, it changes as you go through the galaxy. In fact, k depends on s, upon m, upon the local value of the projected density, upon the local value of the velocity dispersion (which is not surprising), and upon the local value of the frequency of motion, $2\pi/\kappa$, of the star in a Lindblad epicycle. For a given m and s you can ask what the wavelength of the disturbances ought to be. But even before one does that, it is fairly evident that one will come up with something strongly resembling *a spiral arm* at the outset. Because, if I ask where the ridges of this pattern will be, I ask in fact where the phase is constant. As you can see, it is a constant were $\varphi = \varphi_0 - st/m - k\tilde{\omega}/m\epsilon$. And, remembering that k is a function of $\tilde{\omega}$ itself, you can see that this gives you a spiral, provided that k does

not change sign. So this spirality of the answer comes out at once, and there is no getting away from this, except for a consideration to which I will come later (Section 5).

The second thing is that one gets such travelling spiral density waves rotating with a constant angular velocity, which is not necessarily that of the galaxy itself at any point. The shapes of these arms are quite definitely determined.

And now we come to the next point. Because what I have done here, or rather what C.C. Lin has done here, is to look at an asymptotic solution of the equation of the WKB method. As is well known, if one uses the WKB method, one must avoid *turning points*, because there the conditions under which this method applies break down. It turns out that these conditions break down if the quantity $s + m\Omega$, where Ω is the angular circular velocity of the galaxy, is equal to the average angular velocity in the epicycle, κ. I shall attempt to show you why this is a particularly important point. Of course $s + m\Omega$ is a function of the distance and κ is a function of the distance as well. Let us then examine what happens at the point where the two quantities become equal, and we have the so-called Lindblad resonance.

4. THE LINDBLAD RESONANCE

We consider the motion of a particular star which at time $t = 0$ is in S (Figure 2). I will suppose that at that time there are in the neighborhood of the star two spiral arms, indicated by A and B, A being quite close, B further away. Let us now take a later time, t', at which the star has just completed a revolution in its epicycle. Therefore $t' = 2\pi/\kappa$. During this time the center of the epicycle will have moved over an angle $2\pi\Omega/\kappa$ in the direction of the heavy arrow, and the epicycle will have come, for example, to the position indicated by the small dashed ellipse. The star will be at S′. During the time t' the spiral pattern, which, as we have seen, rotates with an angular velocity $-s/m$, will have turned over an angle $-2\pi s/\kappa m$; the arms A and B will now be at the positions marked by the dashed curves A′ and B′. It may happen that at the time t' spiral arm B′ passes through the center P′ of the epicycle at the time, in the same way as A passed through the center P of the epicycle at $t = 0$. Now the distance between two successive intersections of spiral arms with the circle PQP′ is $2\pi/m$. The coincidence mentioned will therefore happen if

$$- 2\pi s/\kappa m + 2\pi/m = 2\pi\Omega/\kappa,$$

or

$$\kappa = s + m\Omega.$$

If this equality occurs, every time the star comes back to the same position in its epicycle it is kicked by a spiral arm. It would not be surprising if something special would happen under these circumstances. And indeed it does: the solution gets very difficult, and one has not yet succeeded in guiding it properly through this Lindblad resonance. But one expects interesting things to happen, depending on whether you are inside the Lindblad resonance, or outside, or in between. So this coincidence, which one can quite clearly expect to occur fairly frequently in galaxies, is a vital issue here. Inside the resonance, if I understand C. C. Lin's considerations correctly, one does not expect to see much of a spiral pattern. Outside one expects to see a well-developed spiral pattern, which, as soon as you are a little bit away from the resonance, is given quite accurately

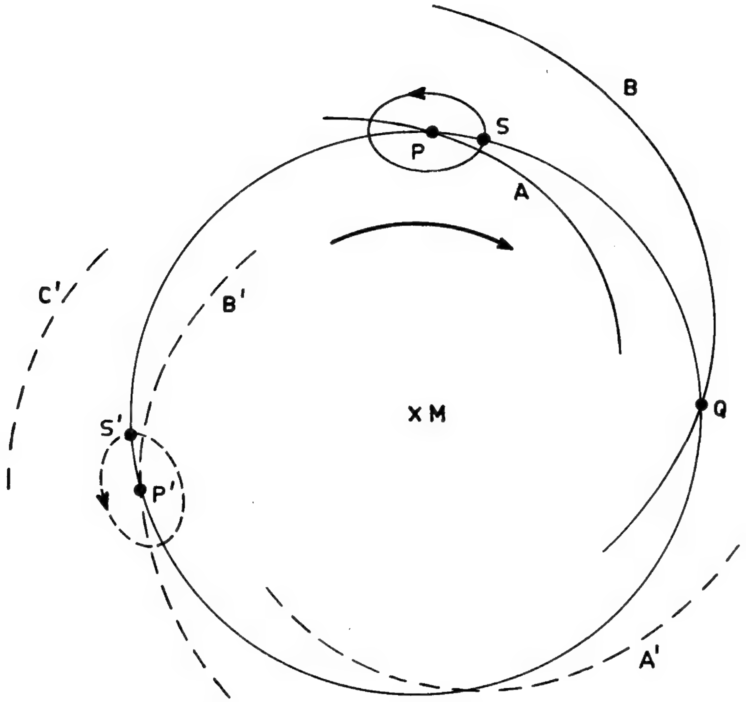

FIG. 2. The Lindblad resonance, see text of Section 4.

by the expression, $\varphi = \varphi_0 - k\,\tilde{\omega}/m\epsilon$. You may or may not eventually come to another Lindblad resonance which terminates the spiral pattern.

This is a very brief and inadequate summary of what amounts, I suppose, in algebra almost to those closely packed digits which Westerhout (Paper 28) presented: there is a tremendous pile of algebra involved.

5. IS SPIRAL STRUCTURE INEVITABLE?

The next thing I want to mention is whether or not it is inevitable that you get a spiral. A number of us have sometimes been worried by something which Lynden-Bell calls the *anti-spiral theorem*. This is the following effect. In many of the simple systems that you can consider, let us say a rotating disk of gas, you can show, because of the structure of the equations, that if you can get a leading spiral, you get a trailing spiral as well: you find practically the same feature the other way around. And from some points of view the most natural classification of the normal mode perhaps does not give spirals but gives what I should call *wagon wheels*, that is, the density is up in some places and down in others. And one would have to superpose these in order to get spirals. At first this sounds like a devastating conclusion, but this symmetry property in the equations means only one thing: the system is too simple. Whenever you see a symmetry property, all you

have to do is mess up the system a little bit and give up the symmetry. There are a large number of things that will *remove the symmetry*, including the following: after all, things were not always like this (the initial conditions will in general have been quite asymmetrical), things were not perfectly friction-free (so there has been dissipation), there is a magnetic field, there may be a little bit of outflow, there may be quite a bit of inflow, from what I have been told; in short, there is non-conservation of everything. This will break the symmetry, and I expect hopefully to find that the natural way to get the arms is trailing. Presumably that would be a direction that would be given in some of these cases by an increase of entropy, whereas the other one would give a decrease. I would like to say that, so far as I know, Lin does not check to see whether or not in his strictly stellar case—which, in so far as the details are concerned, is infinitely messier than the one I have sketched here—this consideration holds. It may be that in the stellar case it does not hold; one does not know at all.

6. SMALLER-SCALE STRUCTURE

Having discussed an attempt to explain the large-scale structures in galaxies I will now say something about attempts which are on a somewhat local scale. We examine a small portion of the galaxy, and see what happens to that. Lynden-Bell and Goldreich, and also Toomre, have studied a rather simple medium of the following sort. Suppose we have a system which is rotating and simultaneously sheared. Locally there is, of course, nothing wrong with representing the velocity field in our galaxy as just that. Suppose you now lay down as an initial perturbation a pattern of waves, and ask what happens to those waves. In both the stellar and the gaseous case what appears to happen is the following sequence of events.

We start with some quite modest perturbation of a wavelength considerably smaller than the galaxy. At a later time one finds that these waves begin to grow quite strongly in amplitude, and that they are oriented more or less towards the center of the galaxy. This is not the time when they reach their maximum strength, it is simply the time when their amplitude is growing most rapidly. And as time increases, one finds that the waves turn over very obediently and start to trail. I may have drawn the wavelength quite short, but I think one can see the picture. These waves will by now have reached a very considerable amplitude. At one point you may see an enormous density perturbation with not much velocity; a little later you see an enormous velocity perturbation with not much density. In favorable cases the growth of the initial perturbations to the state of maximum amplitude is quite impressive, and that makes you wonder about the linearized analysis which one has been using. In order to continue the problem you must then do something non-linear, or you must simply publish the results. The authors mentioned did something non-linear, though of course they did not reach a complete solution. But one can say that these waves, in sweeping up mass from the surroundings, had to grow to a large amplitude, and then shear over to the trailing direction. While one can see that that must happen, one cannot easily see what happens after that. They may have grown to the point where one needs non-linear theories, or a simple shear approximation may still suffice. In this analysis, as originally done by Lynden-Bell and Goldreich, and also by Toomre and others, there are interesting features, which led them to the belief that even more interesting sorts of waves might be permitted if they could only do away with some simple conservation theorem. And the latest work which I have seen

invokes a magnetic field, in the hope that one can tap a secular instability, that is, one which brings the system gradually to a lower-energy state (which is forbidden if there is no dissipation whatever).

7. NON-LINEAR STUDIES

I would now like to mention some of the non-linear work. Whatever one says about the stars, there is not the slightest question but that the density variation of the gas has to increase in a degree which can no longer be treated as small deviations. When you make a 21-cm map, you find far more hydrogen in the arms than you find between them, and you obviously have a non-linear problem. The work that I am now going to report is due to Fujimoto, and does not really attempt to answer the question: why do we have spiral arms? It is an attempt to answer the following question: Granted that there is a certain gravitational disturbance associated with a spiral arm, how does this affect the motion of the gas? And as usual one has to simplify the problem beyond all recognition to get anywhere. The way of doing this is the following.

Let us suppose one has a rotating system and a *gravitational washboard*, that is, a disturbance in the gravitational potential of a sinusoidal form. Now somewhere we will have to make an assumption about the direction in which these gravitational arms move. I will take the direction to the galactic center as indicated in Figure 3, to get a trailed gravitational disturbance. And in response to this, without the perturbation, one would expect the material to move along the line drawn in the figure; i.e., if there were no gravitational washboard, it would get streaming at right angles to the direction of the center of the Galaxy. Given the gravitational washboard, then what happens to the gas? The answer is that the streamlines of the gas—instead of being straight lines, in this model corresponding to a perfect circular orbit—become somewhat cusped. In every cusp there is a shock; and in that shock the density increases, even for a very modest gravitational washboard, by an enormous factor; let us say five or more. The density distribution and the gravitational field will therefore follow a curve like that in Figure 4. I am not exaggerating the density contrast. It is interesting that the gas density comes down to a reasonably low value just a little bit after the shock. It is also interesting that it happens to pile up at places where you should have assumed that the gravitational potential would have a minimum. This is something that you have no right to expect, but it says that under these conditions the gas density reinforces the stellar density perturbation which you had to invoke to produce this gravitional washboard.

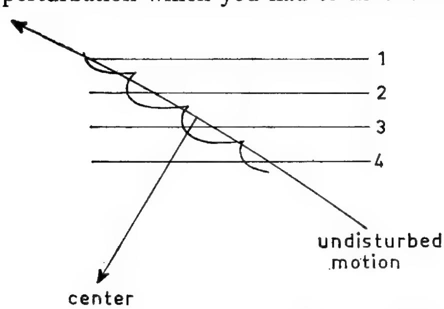

FIG. 3. Motion of gas across a gravitational washboard.

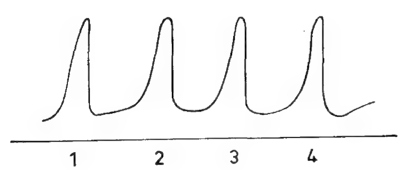

FIG. 4. Density distribution in the gas resulting from the gravitational washboard of Figure 3.

This is one of a very large number of solutions of this non-linear problem; the others, which are not necessarily periodic, or even interesting, have not been examined in this discussion.

Another non-linear attempt at this problem has been made by Helfer. You will hear him discuss this later on today (Paper 53); I will therefore not attempt to summarize it at this moment. He has been interested again in initial-value questions, and the question how long it takes a particular perturbation to grow into a non-linear regime, and when or if you expect discontinuities to develop.

8. CONCLUDING REMARKS

So far I have been talking about rather formal developments, which – after listening to the papers of the last three days – requires, I would say, quite a bit of nerve. The problems that one has been attacking are ones that leave out of consideration a rather large number of mechanisms which may or may not be present in the Galaxy. For example, I would have at this moment no idea what to do with the large amount of material that seems to be flowing into the disk from outside, with zero angular momentum. It might, or it might not, be useful for making spiral arms; it might make the problem easier, or it might not.

Again, I can in this report only briefly mention that some work has been done on the magnetic field; for the gas this is certainly a very important matter, and one does not really have the analogues of these discussions developed well enough for the cases with and without a magnetic field. In addition I could ask: what happens if you add any other mechanisms that are very likely present in the Galaxy, if you look for a sufficiently long time? For example, it is all very well to try to make a spiral-arm theory to last for many rotation periods, but one can ask whether the general structure of the Galaxy itself remains unchanged for so long. There may be a secular inflow of material, there may be an occasional explosion of rather formidable extent; and all these may eventually wind up the spiral-arm pattern.

The last thing I wish to inquire about is: *what consequences has the existence of spiral arms*? One would like to know, for example, what a gravitational washboard *does* to help the stars relax, or whether the succession of shocks, one after another, of the gas ever contributes to a gradual inflow or outflow. Some of these things may be studied with the aid of the 21-cm observations. In looking at these we should pay attention to the circumstance that any coherent structure in the gas should be accompanied by about an equally coherent structure in the velocity field of this gas. Such things have already been suggested by the results that were presented about flow of gas along the outer edge of a spiral arm (Shane, Paper 29); data of this kind may sometime become useful for putting numbers into our theories.

Discussion

F. D. Kahn: Would Lynden-Bell please state precisely his theorem concerning impossible spiral arms?

D. Lynden-Bell: The ***anti-spiral theorem*** is as follows, For a gas obeying the equation of state

$$\frac{\Delta P}{P} = \Gamma(x, y, z)\,\frac{\Delta \rho}{\rho} \quad ,$$

where Δ is the Lagrangian change following a perturbation. Then, provided the unperturbed state is axially symmetrical and provided the unperturbed motion is solely in circles about the axis, it is possible to choose a set of linearized normal modes such that all stable normal modes are of wagon-wheel type. Furthermore, stable spiral normal modes can only exist if two modes of the same symmetry type have the same frequency. Two wagon-wheel modes W_1 and W_2 can then be combined into the spiral mode $W_1 + iW_2$, but this has a conjugate mode $W_1 - iW_2$, which leads wherever $W_1 + iW_2$ trails and vice versa. This theorem is proved in the absence of dissipation and magnetic fields.

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52. DENSITY WAVES IN DISK GALAXIES

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ABSTRACT

Density waves in the nature of those proposed by B. Lindblad are described by detailed mathematical analysis of collective modes in a disk-like stellar system. The treatment is centered around a hypothesis of quasi-stationary spiral structure. We examine (*a*) the mechanism for the maintenance of this spiral pattern, and (*b*) its consequences on the observable features of the galaxy.

1. GENERAL OBSERVATIONS

In discussing the spiral features of disk galaxies, it is important to note the difference between these two questions: (*a*) the organization of a spiral pattern over the whole disk, and (*b*) the detailed structure of a stretch of an individual arm. This point was clearly made by Oort (1962) in the following words:

> 'In systems with strong differential rotation, such as is found in all non-barred spirals, spiral features are quite natural. Every structural irregularity is likely to be drawn out into a part of a spiral. But *this* is not the phenomenon we must consider. We must consider a spiral structure extending over the whole galaxy, from the nucleus to its outermost part, and consisting of two arms starting from diametrically opposite points. Although this structure is often hopelessly irregular and broken up, the general form of the large-scale phenomenon can be recognized in many nebulae.'

The primary purpose of our present theory is indeed an attempt to explain the grand design over the whole disk. We believe that the mechanism for maintaining this grand design can be described essentially in terms of *density waves* of the general nature discussed by the late Bertil Lindblad.* Gravitational forces are predominant, while hydromagnetic forces can at most play a secondary role. Specifically, we believe that the density waves form a quasi-stationary spiral structure.

A more detailed description of our ideas and conclusions has been published elsewhere (Lin and Shu 1964, 1966). Here we shall only indicate a few high points of the theory, and report on the latest numerical results. The density waves are primarily collective modes in a stellar system, which may be described as a 'gravitational plasma'. Numerical results reported below are based on the simplest form of the theory, but they serve well the purpose of demonstrating the relevance of these density waves to the observed spiral features. Briefly, we conclude that the principal spiral pattern in our Galaxy can be

*For further discussions of the relationship between the present theory and that of Lindblad, see Lin and Shu (1966).

associated with a density wave propagating around the center at an angular speed of about 11 km $\mathrm{sec}^{-1}\,\mathrm{kpc}^{-1}$ in the direction of the general galactic rotation of stars.

2. SELF-SUSTAINED DENSITY WAVES OF A SPIRAL FORM

Spiral patterns in the plane of a disk galaxy may be described by functions of the form

$$F(\tilde{\omega}, \theta, t) = A(\tilde{\omega}) \exp \{\mathrm{i}\,[\omega t - m\theta + \Phi(\tilde{\omega})]\}, \tag{1}$$

where t is the time, $(\tilde{\omega}, \theta)$ are the polar coordinates in the plane, $A(\tilde{\omega})$ is a slowly varying function of $\tilde{\omega}$, $\Phi(\tilde{\omega})$ is a slowly varying (monotonic) function multiplied by a large parameter, ω is a real constant (for neutral waves), and m is an integer. As usual, the real part of the above expression is to be taken. The lines of constant $\mathrm{Re}(F)$ are approximately given by the equation

$$m(\theta - \theta_0) = \Phi(\tilde{\omega}) - \Phi(\tilde{\omega}_0), \tag{2}$$

which represents a spiral pattern with m arms. The pattern given by (1) rotates at an angular velocity

$$\Omega_\mathrm{p} = \omega/m. \tag{3}$$

The radial wave number of the spiral pattern is given by $|\,k(\tilde{\omega})\,|$, where

$$k(\tilde{\omega}) = \Phi'(\tilde{\omega}). \tag{4}$$

If the motion of the stars is in the direction of increasing θ, trailing waves correspond to $k(\tilde{\omega}) < 0$ and leading waves to $k(\tilde{\omega}) > 0$.

It can be shown (see Lin and Shu 1966) that a self-sustained density wave of the general nature of (1) can be obtained through an analysis of small disturbances over a symmetrical disk of stars and gas in differential rotation. These waves have the following properties.

(*a*) They extend essentially over a range of the galactic disk where the condition

$$\Omega - \frac{\kappa}{m} < \Omega_\mathrm{p} < \Omega + \frac{\kappa}{m} \tag{5}$$

is satisfied, where $\Omega(\tilde{\omega})$ is the angular speed of the stars, and $\kappa(\tilde{\omega})$ is the epicyclic frequency. We shall refer to this range as the *principal part* of the spiral pattern. Figure 1 shows that, for $m = 2$, the pattern would extend from $\tilde{\omega} = 4$ kpc outwards without limit, if $\Omega_\mathrm{p} = 11$ km $\mathrm{sec}^{-1}\,\mathrm{kpc}^{-1}$. For other values of m, this principal part would be quite limited in extent.

(*b*) The dispersion relation for such waves is expressible in terms of the wave number $\lambda = 2\pi/|\,k\,|$ and the frequency $\nu = m(\Omega_\mathrm{p} - \Omega)/\kappa$ at which the stars see the gravitational field. This relationship includes an additional parameter, which measures the velocity dispersion of the stars. If the velocity dispersion is barely enough to stabilize the disk against gravitational collapse (Toomre 1964), the dispersion relationship is as shown in Figure 2, where $\lambda_* = 4\pi^2 G\sigma_*/\kappa^2$, G being the gravitational constant and σ_* being the projected stellar density.

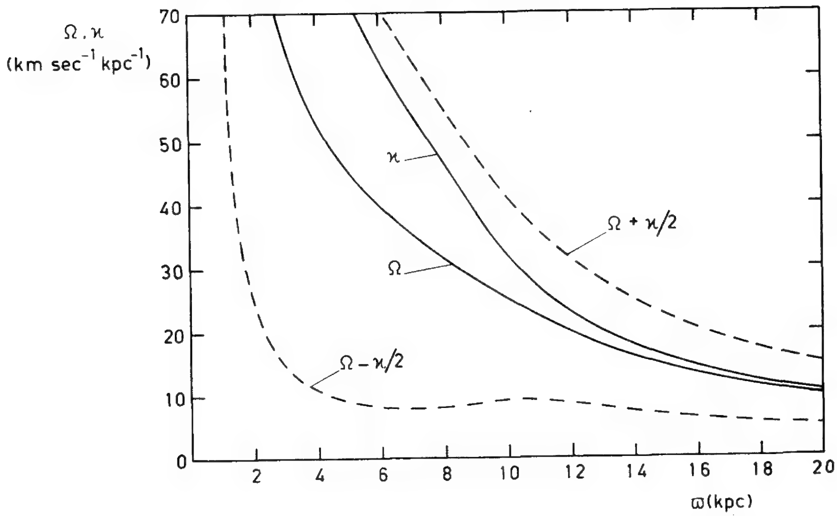

Fig. 1. Angular velocity Ω, epicyclic frequency κ, and related quantities for the 1965 Schmidt model of the Galaxy.

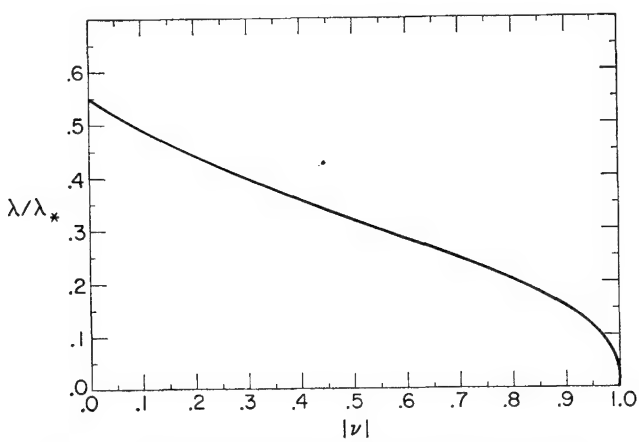

Fig. 2. Dispersion relation for tightly wound spirals.

(*c*) Trailing patterns are preferred over leading patterns, if the velocity dispersion of stars increases toward the center. (Several other effects would also tend to prefer trailing patterns.)

3. AN EXAMPLE OF A COMPUTED PATTERN

By taking $\Omega_p = 11$ km sec^{-1} kpc^{-1}, we get a pattern that starts with a dispersion ring at the Lindblad resonant point, $\tilde{\omega} = 3{\cdot}75$ kpc, and continues with a spiral as shown in Figure 3. This may be compared with the spiral pattern shown by Mrs Burbidge in her Introductory Report (W. Becker 1964, Figure 4).

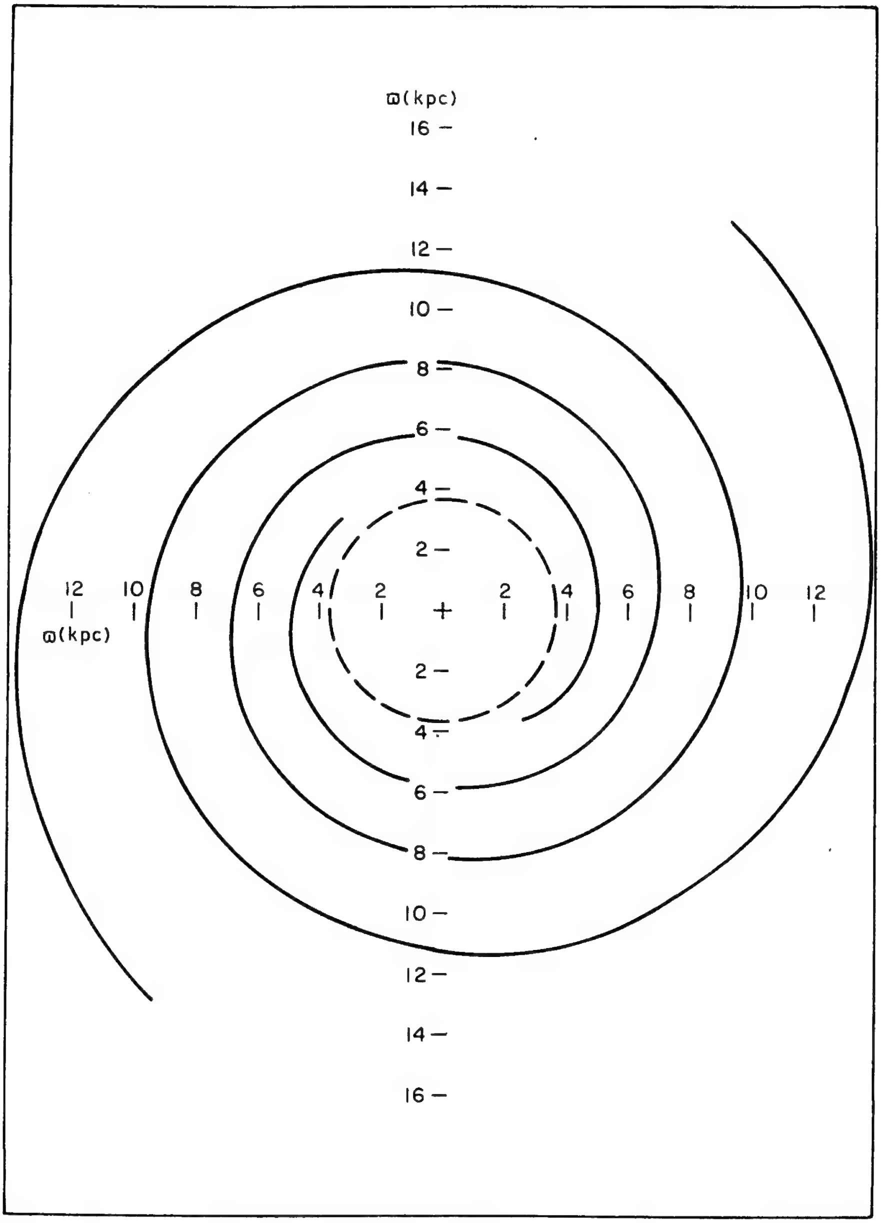

FIG. 3. Spiral pattern calculated for the 1965 Schmidt model, on the assumption that the pattern rotates at an angular velocity of 11 km sec^{-1} kpc^{-1} in the general direction of the rotation. Dispersion ring for Lindblad resonance taken at 3·75 kpc from the center.

No criterion based on the present theory is yet available for determining the pattern frequency. The above value of Ω_p was chosen so that the location of the dispersion ring would correspond to that of the '3-kpc Arm'.* In general, there may be a superposition of a group of waves, and the spiral pattern becomes quasi-stationary. There may also be other spurious spiral arms superposed on the overall pattern. But density waves of the type described appear to be the most natural candidate for the explanation of the existence of a grand design.

REFERENCES

Becker, W. 1964, *Z. Astrophys.*, **58**, 202.
Lin, C. C., Shu, F. H. 1964, *Astrophys. J.*, **140**, 646.
Lin, C. C., Shu, F. H. 1966, *Proc. nat. Acad. Sci. USA*, **55**, 229.
Oort, J. H. 1962, in *Interstellar Matter in Galaxies*, Ed. L. Woltjer, W. A. Benjamin, Inc., New York, p. 234.
Schmidt, M. 1965, in *Galactic Structure*, Eds. A. Blaauw and M. Schmidt, Vol. V in the series: *Stars and Stellar Systems*, Univ. of Chicago Press, Chicago, p. 513.
Toomre, A. 1964, *Astrophys. J.*, **139**, 1217.

Discussion

S. B. Pikel'ner: I should like to know how you avoid the winding of spiral arms in your picture. You have a stable pattern for the density waves, a potential wheel which moves with constant angular velocity. The gas flows across the potential wheel and its density increases in the wheel. The difference between the velocities of gas and wheel must be rather large, of the same order as the rotational velocity, in order to avoid the winding. If the gas density inside the arms is considerably higher than that outside, the velocity of the rarefied gas between arms must be much higher than the differential velocity of gas and wheel. Is this consistent with theory and observations?

C. C. Lin answers: The gas flow velocity required is only a few km/sec in the direction perpendicular to the arms. This is largely because the inclination of the arms with respect to the circular direction is small only: of the order of 5°, or a tenth of a radian. Thus, the required radial velocities are of the order of 1/10 of the velocity differences in the circular direction. Detailed estimation of these velocities, on the basis of reasonable assumptions for the density contrasts, does not indicate any contradiction with theory or observation.

It might be of interest to bring up a related point, namely, the relative motion of the young stars with respect to the gas concentrations. In our neighborhood the stars are moving with a circular velocity of 250 km/sec, whereas the pattern is moving at 110 km/sec (if we adopt the value used for our pattern calculations). This difference in speed would cause a separation of only 140 pc (in the direction perpendicular to the arms, i.e., almost in the radial direction) between the gas concentration and the stellar arm as delineated by stars of the age 10 million years. Older stars would merge into the general population and cannot clearly mark out a spiral arm.

* This is, however, not a very accurate determination, and the value of Ω_p could be as high as 20 km $\sec^{-1}$ kpc^{-1}.

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53. ON THE DEVELOPMENT OF NON-CIRCULAR MOTIONS IN THE GALAXY

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ABSTRACT

An approximate analytic solution of the non-linear equations governing the large-scale galactic dynamics of the interstellar medium is discussed. Non-circular orbital motion results in the rapid development of spiral-like loci upon which the fluid velocity and density tend to become multi-valued. For some simple cases, properties of these loci and of the fluid in their vicinity are given.

I have assumed, on the basis of the 21-cm observations, that in the interstellar medium there are large-scale deviations from circular motion. I have started with a flattened galaxy, characterized by a density $\rho_0(r)$ and a circular velocity $V_0(r)$, both given as functions of radius r, and assumed that at time $t \approx 0$ there exist velocity and density perturbations dependent upon t, r and azimuth θ. The density perturbation is represented by the variable $u_\rho = c_0 \ln [(\rho_0 + \delta\rho)/\rho_0]$, where c_0 is the velocity of sound, and all velocities are measured in units of the maximum of $V_0(r)$ so that all the perturbations are small quantities. I have obtained an analytic solution for the non-linear equations, correct to terms of second order in the amplitudes of the perturbations, using the explicit assumption that the characteristic wave-propagation velocity of a perturbation is amplitude-dependent. Only motions in the galactic plane were considered, and I shall limit discussion to those perturbations which result in nearly-sonic or supersonic streaming. For the self-gravitational interaction, I have used Hunter's approximation, that the perturbation in the gravitational potential is given by $\delta U = 4\pi G\, H^2\, \delta\rho$, where H_z is the scale-height in the direction perpendicular to the plane, and $\rho_0\, H_z^2$ is assumed constant. This approximation is poor in regions in which the gas is compressed and one linear dimension is small; therefore I want to emphasize that I have not solved Poisson's equation for the perturbation in the gravitational potential.

The solution obtained is rather complicated; it can be checked in the following way: For $c_0 \to 0$, you get a certain expression for the velocities, which agrees exactly with an exact solution of the non-linear hydrodynamic equations for a rotating pressureless gas, taken in the limit that the perturbations about steady-state circular motion are small. The solution obtained develops a discontinuity: in the Galaxy regions form in which the velocity and density perturbations tend to become multivalued, which is prohibited. The time it takes the discontinuity to arise for the first time depends, of course, on the precise forms of $V_0(r)$ and of the initial perturbation assumed, but in general one can say that a velocity perturbation of 10 km/sec at the solar distance from the galactic center would yield a discontinuity in one or two rotation periods, and the

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motion of the interstellar medium would be substantially affected by the presence of the discontinuity in about another rotation period.

If the velocity perturbation, δu, *in the vicinity of* $t = 0$ is represented by a simple Fourier analysis:

$$\delta u / V_0(r) = \Sigma A_{Nk} \sin\,[Nr/\lambda + k\,(\theta - \Omega t) + \alpha\Omega t + \eta_{Nk}]$$

(where $\alpha\Omega$ is the Lindblad epicycle frequency), and if modal interaction is ignored, each mode separately tries to develop a discontinuity in a characteristic time which depends upon A_{Nk}, k, and the first and second derivatives of $V_0(r)$. This occurs because η_{Nk} is actually dependent upon δu and t. For most reasonable perturbations it appears as if the $k = 0$ or $k = -2$ modes first form the discontinuity. It first arises at isolated interior points in the Galaxy and then grows both inwards and outwards, and more rapidly outwards. The geometry of the developing discontinuity is that of narrow bounded loops, extending $\lambda/2N$ in the radial direction, and stretched along $|k|$ spiral loci. With the exception of the $k = +1$ mode, all of the spirals are 'trailing' spirals. For the $k = -2$ mode, for example, in the non-central regions of the Galaxy, the angle between the tangents to the spirals and the tangents to galactocentric circles amounts to about $5°$ for every 10 km/sec of velocity perturbation adopted. This last statement may be regarded as an observational prediction of this theory of simple progressive wave development.

The density of the gas at the edge of the discontinuity is about e times the unperturbed density $\rho_0(r)$; halfway between the spirals, the density is at a minimum, at about e^{-1} times the unperturbed density. The maximum density contrast is therefore about e^2.

One case of modal interaction has been studied. In this case a major discontinuity develops, similar geometrically to those described in the preceding paragraph, but of finite duration. It is preceded (in time) by other, minor discontinuities, which are fairly short-lived. Since the major discontinuity has a larger phase velocity, the minor discontinuities will appear to be following the major one (if optical phenomena are assumed to mark the discontinuities).

Precise details of the motion of the gas near the edges of the discontinuity are difficult to determine. When the characteristic spirals are inclined by only about $5°$ to the galactocentric circles, the motion of the gas is nearly parallel to the edges of the bounded regions describing the discontinuity, the phase velocity of the discontinuity being about $1\frac{1}{2}$ times the rotational velocity. While the velocity perturbation in effect results in supersonic motion outwards along the spiral arm, the component of motion of the gas perpendicular to the discontinuity surface may not be supersonic at all. In fact, in the case of a single-mode progressive wave development, the motion of the gas relative to the surface of the discontinuity moves the gas away from the developing discontinuity, and no gas (aside from that transported by pressure expansion) actually crosses the surface of the developing discontinuity. In this case, in the lowest approximation, an increase in density is found on either side of a developing discontinuity, the latter itself developing into a hole or cavity in the fluid. For a non-viscous supersonic flow such a situation may actually be possible. If the initial conditions are modified to allow the presence of other modes, and the inclinations of the characteristic spirals are increased, it appears likely that the gas will flow into one side of the discontinuity, forming a shock front. Therefore, while we may conclude that regions of high gas density will be

associated with the edges of the developing discontinuity, it is not at all clear whether regions of low gas density may not be associated with the regions enclosed by the discontinuity.

It is to be emphasized that the subject of this discussion was a second-order approximation solution, and it is not known for how long a time this solution is a valid representation of the exact solution. On the basis of this approximation, however, it appears as if many features of *first*-order solutions of *linearized* equations of motion are only valid for fairly short periods of time (e.g., substantially less than a rotation period for velocity perturbations $\delta u/V_0(r) \approx 0{\cdot}05$).

Some other details of this work are given elsewhere (Helfer 1967).

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REFERENCE

Helfer, H. L. 1967, in 'Gravitational Instability and the Formation of Stars and Galactic Structures', Quatorzième Colloque int. Astrophys. Liège, *Mém. Soc. R. Liège,* in press.

I.A.U. Symposium no. 31, 1967

54. PLACES OF FORMATION OF YOUNG AND MODERATELY YOUNG STARS

(Invited Paper, introducing the Discussion on Spiral Structure of the Galaxy)

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ABSTRACT

Narrow-band photoelectric photometry can furnish classification indices allowing accurate determination of stellar ages. From these ages, together with well-determined space motions, the places of formation of stars, and their relationship to the spiral structure of the Galaxy, may be determined. This procedure has been successfully followed for 52 B8–B9 stars within 200 pc from the Sun. It turns out that seven of these have originated in the Perseus Arm, with local peculiar velocities of about 22 km/sec.

A simple model is developed describing places of star formation in the Perseus Arm and velocities at formation. The distribution of space velocities and of ages for stars formed according to this model appears to be in agreement with observation.

Earlier in this Symposium, Schmidt-Kaler (Paper 25) has presented evidence regarding star formation in our Galaxy. The spatial distribution of very young stars, which have not moved more than a few hundred parsecs since they were formed, demonstrates the concentration of regions of star formation to the spiral arms in our Galaxy.

1. DETERMINATION OF AGES

It has been clear for some time that the study of the connection between star formation and spiral structure could be extended, if it were possible to determine stellar ages for young and moderately young stars with sufficient accuracy, so that their individual places of formation could be computed from their observed space velocities and ages. I believe that we have now reached a situation where age determinations are indeed sufficiently accurate for such discussions pertaining to stars in the age range up to about 500 million years.

Let me refer in this connection to a point made by Lynden-Bell in his report on the formation of the Galaxy (Paper 44). When we restrict ourselves to main-sequence stars, then the stars of a given color, or spectral class, have ages that range from zero to a value which is a function of the color. For certain purposes this type of information regarding the age is adequate, but for our present project we must rely on ages derived from a more accurate determination of the position of a star in the Hertzsprung-Russell diagram.

The accuracy of MK classification as currently carried out by inspection methods in routine fashion is not sufficient for our purpose. A good example are the early A stars of luminosity class V, which populate the whole width of the main-sequence band. However, for the stars with which we are here concerned, the main-sequence stars of spectral classes B and A, pin-pointing in the Hertzsprung-Russell diagram can be

achieved with adequate accuracy through spectral classification based on photo-electrically determined classification indices. I am referring to methods developed by Th. and J. Walraven, by Borgman and Blaauw, and by Crawford and myself (for a recent review see Strömgren 1966*a*).

Calibration of this region of the Hertzsprung-Russell diagram in terms of mass and age has been obtained through extensive calculations of evolutionary sequences by a number of investigators. Kelsall and Strömgren (1966) have computed isochrones valid for six choices of initial chemical composition covering the composition-range of population-I stars. The accuracy of ages determined from photoelectric classification indices (*uvby* and Hβ photometry), on the basis of this calibration, has been discussed by Kelsall and Strömgren (1966) and by Strömgren (1966*b*). For the region within a few tenths of a magnitude of the zero-age main-sequence the isochrones lie relatively close together, and the accuracy of age determination is rather low. We shall, however, limit the present discussion to stars in the upper half of the main-sequence band. There, the accidental errors of the determined ages are less than 10% (p.e.), and there is at present no reason to believe that the systematic errors in the age calibration due to neglecting the influence of factors such as rotation, internal magnetic fields, and mass loss exceed about 20% (rapid rotators are excluded from the discussion). In particular, application of the method of age determination to stars that are members of the same galactic cluster yields ages with a scatter of less than 10% (p.e.). The effects of variations in initial chemical composition upon the determined ages are relatively small for the B and A stars in the upper half of the main-sequence band. Hence the accuracy of age determination found for the cluster stars may be considered applicable to the general case of population-I field stars.

2. DETERMINATION OF PLACES OF FORMATION

Consider a star whose age is 100 million years. If it is at present located within 200 pc, its photometric distance, its proper motion and its radial velocity are generally sufficiently precise for the calculation of space-velocity components to an accuracy of about 2 km/sec. Referring to Section 1 we can assume that the age is accurate to about 15 million years. For the typical case of a star moving with a speed of 10 km/sec relative to the local standard of rest, we then find that the radius of uncertainty of the computed place of formation is a few hundred parsecs. Since the expected separation of spiral arms in the relevant part of our Galaxy is a few thousand parsecs, this accuracy is adequate for the study of the relation of places of formation to spiral-arm structure. Indeed, the accuracy is sufficient even in the case of stars of somewhat higher age. However, when the age is more than 400 to 500 million years, the uncertainties of the places of formation become too large.

Clearly, for the results of the discussion to throw light on problems of star formation outside our own spiral arm as well as in our arm, we must consider stars with ages larger than about one-half of the Lindblad-epicycle period at our distance from the center of the Galaxy. Thus we are led to study, first, the computed places of formation for stars with ages in the range 80 to 200 million years.

In the upper half of the main-sequence band this age range corresponds to the spectral range B8–B9. Crawford (1958) has carried out photoelectric Hβ and *UBV* photometry for B8 and B9 stars brighter than $V = 6^{m}_{\cdot}5$ and north of declination $-20°$. We can combine the results of this photoelectric photometry with the age calibration by Kelsall

and Strömgren (1966) for stars in the upper half of the main-sequence band. If we limit ourselves to stars within 200 pc, in order to reduce the influence of the proper-motion uncertainties, we find that the necessary data are available for a sample of 52 stars in the age range 80 to 200 million years. Of these stars, 20 are within 120 pc, with correspondingly higher accuracy of the space-velocity data.

For the 52 stars of the sample we computed the places of formation, using the galactic gravitational field adopted by Contopoulos and Strömgren (1965) in their calculation of tables of plane galactic orbits. We consider first the computed distances R from the galactic center to the places of formation. We find that 45 out of the sample of 52 stars have $9{\cdot}4 < R < 11{\cdot}4$ kpc. In the sample of 20 stars within 120 pc, 17 stars have $9{\cdot}4 < R < 11{\cdot}3$ kpc. If we correct the R-distribution for the effect of accidental errors (probable error of R about 0·3 kpc), we find a distribution limited to the range 10·0 to 11·0 kpc.

The seven stars in the sample of 52 which have R definitely outside the range 10 to 11 kpc were all formed further away from the center, with R-values ranging from 12·2 to 13·6 kpc, and averaging 12·8 kpc; for the 3 stars within 120 pc this average is 12·6 kpc. We note that the average age for the 7 stars is 120 million years, less than the average age for the whole sample considered.

Next, we consider the computed velocities in the galactic plane, relative to the local standard of rest at the epoch and place of formation. The average value for all 52 stars is found to be 13 km/sec. For the 7 stars formed with $12{\cdot}2 < R < 13{\cdot}6$ kpc the corresponding value is 22 km/sec. It appears that only a very small fraction of the stars have velocities at the epoch of formation that exceed 24 km/sec.

The sample of stars examined is admittedly small, and while the results suggest certain conclusions regarding star formation and spiral structure, they do not now permit the construction of a definite picture. Let us consider, however, what increase we can expect in the number of stars available for this particular type of discussion. If (*a*) the observations are extended to include the sky south of declination $-20°$; (*b*) the photometry is extended to somewhat fainter stars, to yield a sample of stars in the relevant region of the Hertzsprung-Russell diagram complete to 250 pc distance; and (*c*) radial velocities and proper motions of adequate accuracy are determined for all the stars in question, the sample would comprise more than 200 stars, and the uncertainties caused by the small size of the present sample would be very much reduced.

The results available at present do suggest that the majority of the stars considered were formed in our own spiral arm, and that about 10 to 15% of the stars originated 2 or 3 kpc further away from the galactic center, i.e. in the Perseus Arm. There is in the sample discussed no evidence for a component contributed by star formation in an inner arm.

3. STAR FORMATION IN THE PERSEUS ARM

a. Younger stars (ages smaller than 200 *million years)*

I should now like to pursue the discussion of the category of stars for which the computed values of R are definitely larger than 10·0 to 11·0 kpc. It is characteristic of these stars that their present observed space velocities with respect to the local standard of rest have V-components (in the direction of galactic rotation) in the range $+18$ to $+24$ km/sec. The U-components (which we define as positive in the direction toward the galactic center) range from -2 to $+28$ km/sec. However, the corresponding

velocities in the plane at the epoch of formation are considerably smaller, averaging 22 km/sec as already stated. (Let me mention in passing that Sirius belongs to this category of stars. Since it is close to the zero-age line, its age—presumably about 100 million years—is not well determined, and Sirius is not included in the sample of stars discussed.)

Consider a star, at present close to the Sun, with $U = +20$ km/sec, $V = +20$ km/sec, and $W = 0$. Table 1, an excerpt from the tables of plane galactic motion by Contopoulos and Strömgren (1965), shows the values of R and V_E, the velocity at the epoch of formation relative to the local standard of rest, as a function of time in the past.

Table 1

Past values of galactocentric distance, R, and local peculiar velocity, V_E

(for a star whose present space velocity has the components $U = +20$, $V = +20$, $W = 0$ km/sec)

Epoch (million years)	R (kpc)	V_E (km/sec)
0	10·00	28·3
− 20	10·58	36·0
− 40	11·34	37·6
− 60	12·06	33·5
− 80	12·61	26·8
− 100	12·92	*21·1*
− 120	12·96	*20·1*
− 140	12·73	24·8
− 160	12·25	31·6
− 180	11·57	36·8
− 200	10·81	37·2
− 220	10·14	31·0
− 240	9·83	24·1
− 260	10·03	28·8
− 280	10·63	36·3
− 300	11·39	37·4
− 320	12·10	33·1
− 340	12·63	26·4
− 360	12·93	*20·8*
− 380	12·95	*20·2*
− 400	12·71	25·2
− 420	12·21	32·0
− 440	11·53	37·0

In this table values of V_E smaller than 24 km/sec have been italicized. We conclude that the stars with the space velocity considered, and formed in the Perseus Arm with velocities at the epoch of formation smaller than 24 km/sec, will show up in our neighborhood in distinct showers, separated in time by periods corresponding to the Lindblad-epicycle period.

b. Older stars (ages up to 500 million years)

It is clear that it would be of interest to extend the discussion to stars with ages up to 400 or 500 million years. However, for an age of 400 million years a systematic error in the ages of, say, 15% (which is possible) would lead to appreciable errors in the computed places of formation. At present it therefore seems advisable to follow, in a discussion of the observational material pertaining to stars with ages over 200 million years, a deductive approach rather than the inductive approach chosen for the ages 80 to 200 million years.

As an example, let us consider a model of star formation in the Perseus Arm, defined by the following assumptions. (1) Star formation takes place in a spiral arm with, in the direction of the anticenter, $12{\cdot}0 < R < 13{\cdot}0$ kpc; at the present epoch the spiral is assumed to be trailing, and logarithmic with a pitch angle of 12°. (2) As seen from the galactic center, the spiral arm is at present limited to the left (higher-longitude) side, extending 10° in this direction; on the right side, no limitation is assumed. (3) The velocities V_E at the epoch of formation are smaller than 24 km/sec. (4) The change with time of the spiral-arm pattern is of the Lin-type (cf. Paper 52), i.e., the spiral pattern has rigid rotation with an angular velocity Ω; in our model we choose $\Omega = 20$ km sec^{-1} kpc^{-1}.

In defining the model of this example we have clearly been guided by (1) the results on the structure of the Perseus Arm derived from 21-cm observations, as presented at this Symposium by Lindblad (Paper 24); (2) the corresponding results from galactic-cluster investigations by W. Becker and his collaborators, cf. Schmidt-Kaler's discussion (Paper 25); (3) the results obtained from our discussion of the 80- to 200-million years age group; and (4) the theoretical discussion by Lin (Paper 52).

Using the tables of plane galactic orbits by Contopoulos and Strömgren (1965) we derive, for our model, the results shown in Table 2. For given values of the space velocity (U, V) relative to the local standard of rest, as observed at the present epoch, the table indicates the range of possible values of R (in kpc) at the epoch of formation. Furthermore, it contains the average value of the angle θ'. This angle (counted positive clockwise) is measured at the galactic center from the direction $l^{II} = 180°$ to the direction of the place of formation, after the latter has been rotated through an angle given by the Lin-pattern angular velocity Ω times the age of the star. In other words, the angle θ' defines what would be the present location of the place of formation, if it had moved with the spiral-arm pattern through the lifetime of the star. Finally, Table 2 gives the range of possible travel times from the epoch of formation to the appearance of the star at our position at the present epoch, i.e. the range of stellar ages (in million years). The data in Table 2 refer to what we have called the second shower (cf. Table 1) from the model Perseus Arm.

In our discussion of Table 2 we limit ourselves to a summary of the results of comparison with observation. The distribution of space velocities in the (U, V) plane for stars in the age range 300 to 450 million years has been investigated by Strömgren (1963, 1967). He finds that the region in the (U, V) plane which, according to Table 2, should contain Perseus-Arm stars, is indeed populated by a substantial fraction of the stars (more than 20%), which form a distribution separate from the main distribution around $U = 0$, $V = 0$. We note that the region in question contains the nucleus stars of the Ursa Major Stream. The phenomenon appears in earlier discussions of the kinematics of A stars by Delhaye and Blaauw, and is clearly shown in Eggen's (1963) discussion of the (U, V) diagram for A stars.

Table 2

Star formation in the Perseus Arm

Places and times of formation for stars which at present have velocities (U, V) with respect to the local standard of rest.

V (km/sec) U (km/sec)	+18	+20	+22	+24	+26
0	n.c.	n.c.	n.c.	n.c.	n.c.
+4	n.c.	n.c.	12·8–13·0 −9° 410–420	13·2–13·3 −8° 370–390	n.c.
+8	n.c.	n.c.	12·9–13·0 −8° 400–410	13·2–13·3 −8° 370–380	n.c.
+12	n.c.	n.c.	12·9–13·1 −6° 390–410	n.c.	n.c.
+16	n.c.	n.c.	13·1–13·2 −7° 370–390	n.c.	n.c.
+20	n.c.	12·9–13·0 −9° 380–390	13·2–13·3 −7° 360–370	n.c.	n.c.
+24	n.c.	13·0–13·1 −7° 380–390	n.c.	n.c.	n.c.
+28	n.c.	13·2–13·3 −7° 360–370	n.c.	n.c.	n.c.
+32	13·0–13·1 −8° 360–370	n.c.	n.c.	n.c.	n.c.
+36	n.c.	n.c.	n.c.	n.c.	n.c.

Note: Space velocities (U, V) for which there is no contribution from the model Perseus Arm (second shower, cf. Table 1 and its discussion in Section 3*a*) are marked n.c. All space velocities with negative U-values, and all with $V > +26$ or $V < +18$ km/sec belong to this category. For other space velocities (U, V) the following three quantities are listed: R (in kpc), θ', and travel times (in million years), see text.

Strömgren also finds that there is a gap in the ages of Perseus-Arm stars, between 150 and 300 million years, in sufficiently good agreement with the predictions of the model.

We must emphasize that again the sample is small: about 40 stars in the age range 300 to 450 million years. Here, however, the available photoelectric *uvby* and Hβ photometry is complete only to $V = 5^{m}.0$ and north of declination $-10°$, and the size of the sample can easily be increased by a factor of, say, 4 within the next year or two.

It should also be stressed that the observational data can be interpreted in other ways than the one outlined here. If we are willing to accept the idea that a substantial fraction of the stars in the age range 300 to 450 million years are formed with space velocities, relative to the local standard of rest, that are a good deal higher than 24 km/sec, then we are not forced to accept origin in the outer spiral arm.

4. CONCLUDING REMARKS

The material discussed offers possibilities of testing the theory developed by C. C. Lin. If we had not assumed that star formation took place in a spiral-arm pattern that rotates as a solid body, but had assumed instead formation in a big cloud complex moving with circular velocity, we should have concluded that the stars with V in the range $+18$ to $+24$ km/sec came from a region considerably inside and to the left of the observed outer spiral-arm region. This discrepancy is noticeable already for the stars with ages 80 to 200 million years, and it is clearly present for the age range 300 to 450 million years.

The choice of a 'limit to the left' in the model Perseus Arm at $\theta' = -10°$ is necessary in order to explain the almost complete absence in the 300- to 450-million year sample of stars with V between $+18$ and $+24$ km/sec and with negative values of U.

The adoption of a value for the Lin-parameter Ω substantially smaller than 20 km sec^{-1} kpc^{-1} would give rise to a discrepancy, similar to the one already mentioned for the case of star formation in a cloud complex moving with circular velocity.

In conclusion I suggest that further, considerably extended work on space velocities and ages of young and moderately young stars would be of some help in solving the problems of spiral arms in our Galaxy.

REFERENCES

Contopoulos, G., Strömgren, B. 1965, *Tables of Plane Galactic Orbits*, Publ. Inst. Space Studies, Goddard Space Flight Center, NASA, New York, U.S.A.
Crawford, D. L. 1958, *Astrophys. J.*, **128**, 185.
Eggen, O. J. 1963, *Astr. J.*, **68**, 697.
Kelsall, T., Strömgren, B. 1966, *Vistas in Astronomy*, **8**, 159.
Strömgren, B. 1963, *Q. J. R. astr. Soc.*, **4**, 8.
Strömgren, B. 1966*a*, *A. Rev. Astr. Astrophys.*, **4**, 433.
Strömgren, B. 1966*b*, in *Stellar Evolution*, Eds. R. F. Stein and A. G. W. Cameron, Plenum Press, New York, U.S.A., p. 391.
Strömgren, B. 1967, *Astr. J.*, in preparation (Russell Lecture).

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55. DISCUSSION ON PROBLEMS OF SPIRAL STRUCTURE*

A. Blaauw: In connection with Strömgren's observation (Paper 54) of a systematic shift of the places of origin of the 'Perseus-Arm' stars ($\langle R \rangle \approx 12$ kpc, ages 100 to 200 million years) toward the 'following' side of the present Perseus Arm, it may be of interest to notice that also in our neighbourhood the positions of the clusters with earliest types B3-B5 are shifted to the 'following' side of the Orion Arm with respect to the O-B2 clusters.

Th. Schmidt-Kaler adds: There is more evidence for this phenomenon. When plotting dwarf emission B stars you find that the older dB2e and dB3e stars tend to fall in the region left of the actual spiral features, and the more so the older they are. The same is true for the less luminous (older) Cepheids. In this regard one should remember also the very strong nearby concentration of late B and early A stars in Carina, a fact which has been stressed often by Bok.

Blaauw asks Strömgren: To what extent may your present data concerning age, motion and possible places of formation be used to check on the validity of the currently used values for the force $K(z)$?

B. Strömgren answers: Similar observational material, but derived for stars of later spectral class, should be quite useful for this purpose.

In this connection, I should like to remark that discussion of the oscillations at right angles to the galactic plane on the basis of observed ages and space velocities for individual stars might yield interesting results, particularly for the young stars.

H. L. Helfer asks Strömgren: Do I understand correctly that, for your seven stars originating in the Perseus Arm at $R \approx 12{\cdot}8$ kpc, their average peculiar velocity with respect to the local standard of rest of the Perseus Arm at their time of origin was 22 km/sec?

Strömgren: Yes, 22 km/sec. As Van Wijk showed several years ago, when you have a star that moves, say, from the next outer spiral arm to our neighbourhood, then there is an increase in the speed relative to the local standard of rest by a factor of about 1·5. Therefore, in this case the average peculiar velocity at formation is considerably smaller than the average velocity for the same stars as observed at the present epoch.

B. Westerlund: Miss Lindsey F. Smith at Mount Stromlo Observatory has recently studied the galactic distribution of the Wolf-Rayet stars. These stars have very high luminosities and can be identified over distances up to 10 kpc from the Sun. As Schmidt-Kaler's diagrams (Paper 25, Figures 4a, b) showed, most optical investigations are limited to the region within about 3 kpc of the Sun.

*In the Symposium programme, this discussion was combined with an overall-discussion concluding Part II of the Symposium. The few discussion contributions which fell outside the scope of the present chapter have been moved elsewhere (Papers 29 and 50).—*Editor.*

The Wolf-Rayet stars show concentrations near the tangential directions of the Carina-Cygnus Arm and of the Sagittarius Arm as defined by the 21-cm observations of neutral hydrogen. Their general distribution in these directions is suggestive of circular arms. No Wolf-Rayet stars have so far been found in the anti-centre direction.

A comparison between the distributions of the subclasses of the Wolf-Rayet stars in our Galaxy and in the Large Magellanic Cloud (LMC) shows that the subclasses which are poorly represented in the LMC, are concentrated to the region within 9 kpc of the galactic centre. In particular, all ten members of the subclass WC9, which is not at all represented in the LMC, fall within 7 kpc of the galactic centre. This class is believed to represent the oldest types of Wolf-Rayet stars, and we have thus an indication of a difference in age between Population I inside and outside the Sagittarius Arm.

T. K. Menon: I had occasion two months ago to see some photographs of Sb and Sc galaxies taken with a narrow-band Hα filter by Morgan of Yerkes Observatory. The outstanding feature of these Hα photographs was the extreme narrowness and regularity of the spiral arms as compared to the continuum blue photographs of the same galaxies which showed rather wide and irregular spiral structure. One got the impression that the two kinds of photographs showed spiral structure of different ages in the same galaxy. I should like to call the attention of theoreticians to these sets of photographs.

H. M. Tovmasjan: In connection with these considerations of the development of spiral structure, I should like to note that from optical and radio investigations of the nuclei of barred galaxies one gets the impression that the nuclei of SBa galaxies are younger than those of SBc galaxies. If this conclusion is valid, and if consequently SBa galaxies are themselves younger than SBc galaxies, then the possibility of such an inverse evolution of spiral structure must also be considered.

B. J. Bok: I have several questions to ask our theoreticians.

(*a*) What observational data are most needed to check the theoretical work by Prendergast, Lin and Helfer?

(*b*) Do they suggest that we should more or less ignore the presence of magnetic fields, and should we no longer consider the magnetic approach to spiral structure?

(*c*) Is there a natural explanation in the gravitational theories for the existence of magnetic fields oriented along the spiral arms?

(*d*) Is there a natural explanation for the barred spirals in terms of the gravitational theories?

K. H. Prendergast answers:

(*a*) In order to check the density-wave theory against observations it is vital to know the tilt of the arms and the spacing between them. The theory also requires us to know the velocity dispersion of the stars, the density integrated through the plane, and the velocity of rotation, all these as functions of the distance from the center.

So far as the behaviour of the gas is concerned, the observations of Shane and Burton (Paper 29) are particularly interesting. In general we should expect that the gas will exhibit systematic motions in the neighbourhood of a coherent structure like a spiral arm, and these motions should be looked for.

(*b*) The magnetic field should be important in determining the motion of the gas, and will have to be included in the theory eventually.

(*d*) The barred spirals are a somewhat different case, since they have a highly non-axisymmetric gravitational field (that of the bar), and this dominates the motion. For an ordinary spiral the departures from axisymmetry are small and their effects are more subtle.

H. L. Helfer adds:

(*a*) I would say the most promising observational approach is to get a correlation between deviations from circular motion and pitch angles of spiral arms.

(*b*) If the magnetic field in spiral arms consists of compressed flux loops, the polarization measurements would be explained and the field would have little dynamical effect. This point has been advanced by Woltjer. It may of course turn out, however, that a purely gravitational theory of spiral structure is deficient, and it may become necessary to incorporate large-scale magnetic-field effects.

(*d*) Prendergast has an unpublished theory of barred spirals which seems very promising.

C. C. Lin answers Bok (this answer was considerably supplemented after the Symposium):

(*b*) We should certainly not ignore the presence of a magnetic field in our Galaxy. However, we need not consider the effect of the magnetic field for the discussion of the spiral pattern in the more massive part of our Galaxy, where the stellar component is predominant. In the outer part, where the gaseous component is predominant, the magnetic field would of course play an increasingly important role.

(*c*) Yes. The natural deduction from the theory presented is that the large-scale magnetic field would be essentially oriented along the spiral arms.

(*d*) Yes. Prendergast has such a theory (see 1962, *The Distribution and Motion of Interstellar Matter in Galaxies*, Ed. L. Woltjer, W. A. Benjamin, Inc., New York, p. 217).

(*a*) The implications are too many to be discussed in a nutshell. Bok and I have agreed to make this a long-term effort of collaboration.

L. Biermann: I suggest that observational data as required for the analysis described by Strömgen are added to the list of desiderata: more complete high-quality data of this kind would clearly be very important for deriving the rotation parameters of the spiral pattern.

D. Lynden-Bell: For any gravitational theory, a theorist wants to know the strength of gravity. We need the total surface-density contrast between the spiral arms and the inter-arm regions.

S. B. Pikel'ner: I am afraid that a pure gravitational theory as discussed here cannot explain spiral arms nor related phenomena, such as barred spirals and intergalactic bridges. There will be great trouble with the explanation of arms in distances from the centre larger than 10 kpc, where the gas density is not small in comparison with the stellar density. Magnetic fields should play a major rather than a secondary role in the theory. The last two years I have tried to explain qualitatively the formation and properties of arms, bars and bridges; magnetic forces dominate in my hypothesis. But the main difficulty, the winding of spiral arms, remains and I admit that it would be necessary to assume a flow of gas across the spiral arms; in other words, to give some synthesis of both theories.

Lin answers: The relative importance of the magnetic field and the gravitational field must be estimated by considering certain dimensionless ratios, such as that between the energy densities in both components. If one refers to standard values, e.g. those given in Allen's *Astrophysical Quantities*, it is clear that, in the more massive parts of disk galaxies, the kinetic energy is far larger than the hydromagnetic energy. In the outer parts, where the stellar density is small, hydromagnetic forces could become important; but this must be checked by a careful examination of the orders of magnitude of the quantities involved.

J. H. Oort asks: What are Lin's further plans for numerical model computations?

Lin answers: At present, we have no immediate plans to extend our work much further before the effect of the thickness of the disk is considered. It is expected that a thickness of a few hundred parsecs might influence scale determinations, when the scale under consideration is of the order of 2 or 3 kpc. In the meantime, we are collaborating with Strömgren on the problem of the migration of stars, to gain a more definite picture of the spiral structure within a few kpc of the Sun.

H. L. Helfer: I do not think that postulating a permanent pattern is absolutely necessary. A relaxation phenomenon could also explain spiral structure, if spiral arms can be made quickly enough. If one can make spiral arms from non-circular motions (cf. Paper 53) in, say, two rotation periods, and if these arms wind up in another rotation period, a new generation of spiral arms would occur in another two rotation periods. Considering the scale of the Galaxy, it would be entirely possible to have both 'old' and 'new' spiral arms existing at the same time in different parts of the Galaxy.

Part III

THE GALAXY AS A RADIO SOURCE; MAGNETIC FIELDS

'The larger one's ignorance, the stronger the magnetic field.'
L. Woltjer, in Paper 80

M

I.A.U. Symposium no. 31, 1967

Chapter III A

Distribution and Spectrum of the Non-Thermal Radiation; the Galactic Halo

CHAIRMAN: G. R. Burbidge

(University of California, San Diego, California, U.S.A.)

'At the moment we are in a happy position where the accuracy of the radio measurements is very much higher than that of cosmic-ray measurements, so we can rest for a while.'

J. E. Baldwin, in Paper 56

56. THE NON-THERMAL RADIO EMISSION FROM THE GALAXY

(Introductory Report)

J. E. BALDWIN

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ABSTRACT

In this review of the non-thermal continuum radiation from the Galaxy, the following issues are discussed:

(1) The non-thermal continuum radiation in the disk.

(2) Evidence for spiral arms in the non-thermal continuum, and the origin of the radiation in sources or in large-scale magnetic fields.

(3) The nature of the spurs extending to high galactic latitudes.

(4) Evidence for the existence or absence of a radio halo.

(5) The galactic radio spectrum and its relation to the cosmic-ray electron spectrum.

(6) Supernova remnants, their structure and spectra.

(7) A comparison of the Galaxy with other normal galaxies.

(8) Observational needs.

1. THE GALACTIC DISK

A *model* of the distribution of the non-thermal continuum radiation in the Galaxy is an important starting point for discussions of many galactic problems. The process of preparing such a model is, unfortunately, not unique and in recent years this fact, rather

than observational discrepancies, has led to some disagreement concerning the distribution of emission in the Galaxy.

Models of the distribution of emission are usually based on the assumptions that the galactic centre is a centre of symmetry and that the galactic plane is a plane of mirror symmetry. The observed symmetry about the galactic equator of the radiation at low latitudes, and the symmetry in longitude about the galactic centre, make these assumptions reasonable ones.

It seems correct to study first the radiation at *low latitudes*, since this provides the brightest and most symmetric features of the observed contours. The consequences of possible disk distributions of emission providing this low-latitude radiation must be fully explored; only then may we profitably discuss what observed radiation remains to be accommodated in some kind of halo or in irregular features.

For simplicity we shall initially ignore spiral structure and seek a smooth symmetric model of the disk. At low galactic latitudes, thermal radiation from ionized hydrogen is known to be important. At frequencies above 1400 MHz the thermal radiation is stronger than the non-thermal, whilst at frequencies below 50 MHz the optical depth of the ionized hydrogen is sufficient to largely determine the observed distribution of emission at low latitudes. Observations at *intermediate frequencies* provide the best information on the non-thermal radiation, and a number of surveys of good resolution and sensitivity are now available at 400 MHz. At this frequency Large *et al.* (1961) showed that at $b = 0°$, for longitudes towards the galactic centre, the thermal radiation contributes about 30% of the total. Its distribution in latitude is, however, much narrower than that of the non-thermal radiation, and at latitudes greater than about $1^{\circ}\!.5$ the thermal radiation is only about 10% of the total. The separation of the thermal and non-thermal radiation depends on assumptions concerning the non-thermal radio spectrum, but the observations at low frequencies, where the absorption due to ionized hydrogen is appreciable, give support to these conclusions. Since the thermal radiation is discussed at greater length elsewhere in this Symposium (Chapter IIC, Papers 36–41), we shall not refer to it again but will use the above values in deducing the properties of the non-thermal disk radiation. Errors in the contribution from thermal radiation lead to uncertainties in the final results which are small compared with those arising from other causes.

The *longitude distribution* of the non-thermal radiation at $b = 0°$ shows a peak at $l = 0°$ and falls to low values at longitudes about $\pm 60°$ from the centre. If we take the distance of the Sun from the galactic centre to be 10 kpc, this implies a *disk* of emission having a radius of about 8·7 kpc. There is some evidence for stronger emission towards the centre of the disk, but the details depend again on the accuracy of the separation of thermal and non-thermal radiation.

Relatively little attention has been paid in the past to the *distribution of the radiation in latitude*. As a simple model for comparison with observations we take a circularly symmetrical disk, stratified in layers parallel to the galactic plane such that the emission per unit volume at height z above the plane is $J(z)$. If the Sun lies just outside such a disk of diameter D, the maximum sky brightness occurs at $l = 0°$, and has the value $DJ(0)/4\pi$. The brightness at latitude b is $\int_0^\infty J(z)\,dz$ cosec b for latitudes sufficiently high that the line of sight passes through the thickness of the disk before reaching the distant edge of the disk. We notice that, for such a model, the distribution in latitude can only

furnish the *equivalent thickness* of the disk, $2\int_0^\infty \mathcal{J}(z)\mathrm{d}z/\mathcal{J}(0)$, and cannot give any indication of the *form* of $\mathcal{J}(z)$.

Combination of three surveys at 400 MHz (Large *et al.* 1961, Seeger *et al.* 1965, Pauliny-Toth and Shakeshaft 1962) yields well-calibrated observations with good resolution over a wide range of latitudes. The variation of temperature with cosec b is shown in Figure 1 for $l = 4°$ (which just avoids the source Sgr A). The observed values give a good fit to a straight line, up to latitudes of about 20°. At higher latitudes the emission falls below this line, indicating low values of $\mathcal{J}$ in the neighbourhood of the Sun. This is in accord with the evidence from the distribution in longitude. There is no clear indication of an increase in $\mathcal{J}$ towards the central plane of the disk, which would be apparent at low latitudes. Taking the non-thermal contribution at $b = 0°$ as 330 °K, and a radius of 8·7 kpc for the disk, we find $\mathcal{J}(0) = 19$ °K kpc^{-1}. The slope of the line in Figure 1 is 7·9 °K per unit of cosec b; allowing for a thermal contribution to this of 10%, we conclude that the equivalent thickness of the disk is 750 pc, with an uncertainty of probably $\pm$100 pc. The *emission per unit volume* may usefully be expressed in several ways:

$$\text{At 400 MHz, } \mathcal{J}(0) = \begin{cases} 19\ °\mathrm{K\ kpc^{-1}} \\ 11 \times 10^{9}\ \mathrm{W\ Hz^{-1}\ pc^{-3}} \\ 4 \times 10^{-39}\ \mathrm{erg\ sec^{-1}\ Hz^{-1}\ cm^{-3}} \end{cases}$$

Study of the distribution of emission at other longitudes confirms this simple picture, in which the Sun is situated just outside a symmetrical disk of emission. For this model the contours of brightness temperature at latitudes greater than say 5° should be parallel to the galactic equator and extend to those longitudes at which the disk is seen tangentially. This effect is apparent in the southern-hemisphere survey at 30 MHz by Mathewson *et al.* (1965), in which at latitudes of 10° to 20°, where the low resolution is unimportant, the

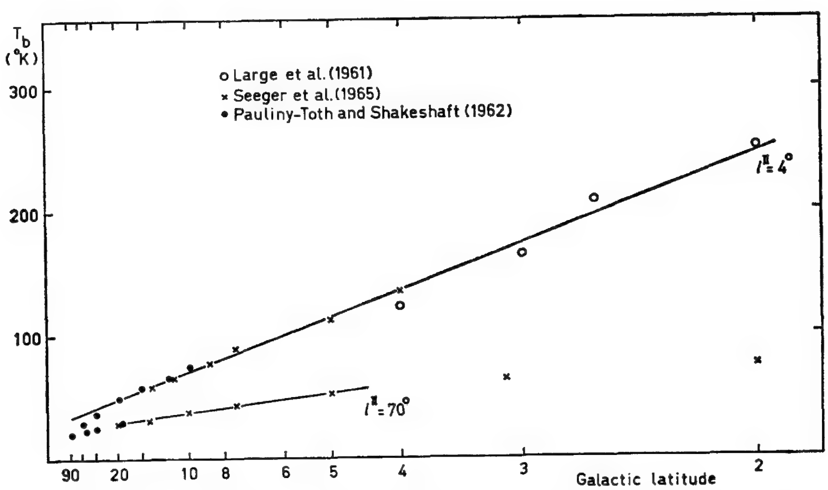

FIG. 1. Brightness temperature T_b at 400 MHz as a function of latitude b (plotted as cosec b), for galactic longitudes $l^{\mathrm{II}} = 4°$ and $l^{\mathrm{II}} = 70°$.

contours lie parallel to the equator out to $l \approx 310°$; in the northern-hemisphere survey at 400 MHz by Seeger *et al.* (1965) a similar effect may be seen extending to $l \approx 50°$. The longitudes of the *tangential directions* cannot be defined exactly but are about 305° and 55°.

We may now examine the evidence for deviations from uniformity in the disk.

2. EMISSION FROM SPIRAL ARMS

The search for excess emission associated with spiral arms has in the past been conducted through studies of the distribution of emission with longitude at $b = 0°$. Where spiral arms are seen tangentially, considerable peaks in the brightness distribution should arise if the emission is isotropic. No very high peaks were found, and this fact was ascribed to anisotropy of the emission, associated with the alignment of magnetic fields along the spiral arms. On this basis, *steps* in the distribution of emission were expected at longitudes corresponding to the tangential directions. There has been little progress in this field since the work of Mathewson *et al.* (1962), who found good correlation of spiral-arm directions indicated by thermal radiation, discrete sources and neutral hydrogen, but no good correlation of these with the non-thermal radiation. Komesaroff (1966), from observations at 408 MHz, has found evidence for a step in the non-thermal radiation at $l = 326°$, not only at $b = 0°$ but extending to $b = \pm 4°$. This he associated with a similar step at $l = 34°$ as giving evidence of a ring-like structure rather than a conventional spiral pattern of the kind proposed by Mills (1959). The width in latitude corresponds to a thickness of 1100 pc, somewhat larger than the thickness of 750 pc derived for the disk model.

The evidence for non-thermal radiation from *spiral or circular features* in the central parts of the disk is thus strong but not conclusive. It is fruitful to study also the region of the local spiral arm corresponding perhaps to the peaks of emission in Cygnus and Carina. We have already noticed that the edge of the disk is seen tangentially at $l = 55°$. This agrees well with the direction of the edge of the Sagittarius Arm, observed at $l = 51°$ by Burton (1966). At slightly greater longitudes the line of sight should lie in an *interarm region* and it is of interest to determine J for such a region. The observations plotted in Figure 1 for $l = 70°$ give a line of much gentler slope and hence a smaller J than those for $l = 4°$. For $b < 5°$ the line of sight probably intersects the local spiral arm at a distance of about 3 kpc, but at higher latitudes the line of sight passes only through the interarm region. Taking the mean slope over the latitude range $5° < b < 20°$ we obtain $J = 6\ °\mathrm{K\ kpc}^{-1}$, a value some three times smaller than the mean for the disk. This could represent merely the decrease of J with increasing distance R from the galactic centre, but there is good evidence for an increase in J at a larger radius R, corresponding to the *local spiral arm*.

The features of the contours of brightness associated with this are readily visible in, for example, the 400-MHz map of Seeger *et al.* (1965). At longitudes close to 180°, where the local spiral arm passes just outside the Sun's distance from the galactic centre and roughly perpendicular to the line of sight, the distribution in latitude is broad ($\pm 20°$) and the intensity relatively low. At longitudes towards Cygnus the arm is seen at a greater distance and it runs at a smaller angle to the line of sight; the distribution in latitude here is narrow ($\pm 5°$) and the brightness high.

In making a model of this spiral arm the most important question to settle is that of the *origin of the radiation.* Does the non-thermal radiation originate mainly *in a smooth*

interstellar magnetic field or in remnants of old supernovae? Both views have had supporters. Mills (1959) showed that, for longitudes towards the galactic centre, the concentration of sources to the galactic equator is much stronger than that of the contours of the non-thermal background. A background formed by the superposition of large numbers of fainter, and on the whole more distant, sources of the same type could not give a distribution in latitude as broad as that observed. Hence sources provide a relatively unimportant contribution to the disk radiation. In contrast, Davies and Hazard (1962), from a study of the anticentre region at 237 MHz, concluded that most of the emission from the disk at these longitudes could be attributed to sources rather than to a smooth continuum.

If the latter view is correct it has important consequences. The radiation observed in any direction then originates from regions of strong magnetic field occupying perhaps only a small fraction of any line of sight. In recent years, attempts to reconcile the observed radiation with measurements both of the flux of cosmic-ray electrons and of upper limits to the interstellar magnetic field have met with difficulties. These might well be resolved in the type of model suggested by Davies and Hazard (1962). This hope I believe to be unfounded, for the following reasons:

(*i*) In their analysis Davies and Hazard first subtracted from their observations a smooth background having an extent of $\pm 25°$ in latitude, which should surely be described as disk radiation.

(*ii*) The radiation is strongly polarized at high frequencies, as much as 25% in some places at 1407 MHz; this situation extends over areas of $60° \times 60°$. This implies a magnetic field organized over large distances.

(*iii*) Those non-thermal sources which are recognized as galactic show a greater concentration to the galactic equator than the contours of brightness, even at longitudes near the galactic anticentre.

(*iv*) The contours of brightness are relatively smooth. For example, in the region of sky near $l = 120°$, $b = +10°$ on the map of Seeger *et al.* (1965), the variation on a scale of one beamwidth (2°) of the total brightness associated with the spiral arm is not greater than 20%. If the background is made up of sources which are less than 2° in diameter, there must be at least 25 sources in each beam if the statistical variations are not to be larger than those observed. Such hypothetical sources would not correspond to those observed individually by Davies and Hazard. They would be much fainter and more numerous and, whilst this possibility cannot be ruled out, there is no independent evidence for their existence.

I hope that the firm statement of this viewpoint will arouse some comment, since the issue is clearly an important one.

Assuming now that the emission arises from cosmic-ray electrons moving in a large-scale interstellar magnetic field, what can we deduce about the *structure of the field*? The main features to be explained by any model are:

(*a*) the distribution of emission in latitude at different longitudes, as discussed earlier;

(*b*) the asymmetry of the contours about the galactic anticentre. The brightness at the equator falls steadily from $l = 90°$ through the anticentre to $l = 220°$;

(*c*) the polarization of the background. This shows a maximum at $l = 160°$, and there is a systematic pattern in the Faraday rotation in this region.

Hoyle and Ireland (1961) proposed a model in which the magnetic field was a helix, tightly wound about the spiral arm and then sheared by differential galactic rotation. This model gave a good description of the distribution of emission along the galactic equator. Hornby (1966) has extended their analysis to all latitudes, and was able to find a model giving a good fit both to the contours of brightness and to the polarization results. He derived a thickness for the arm of about 400 to 800 pc, similar to that of the disk radiation inside the Sun's distance from the centre; the emission per unit volume in the arm, which may be deduced from his work, is also approximately the same as the mean value of J for the disk. This implies that, if the central region of the disk is not smooth but is composed of spiral arms or ring-like structure, then the value of J in them is somewhat greater than for the local spiral arm, but the difference is probably not as large as a factor of 10.

3. THE GALACTIC SPURS

Over the past few years several so-called 'spurs' of radiation have been recognized extending from the galactic equator to high latitudes. Of these the *North Galactic Spur* is by far the most intense. Large *et al.* (1962) have drawn attention to the *Cetus Arc*, and Quigley and Haslam (1965) to a third feature, which they named *Loop III*.

It seems worth while to summarize their *observational properties*, although the following list may be criticized as being an oversimplification.

(*i*) They appear to start from near the galactic equator and to extend to high latitudes. There are no clear cases of a spur *crossing* the galactic equator.

(*ii*) Their brightness, after subtraction of the background in so far as this is possible, falls off with increasing latitude but there is no good evidence regarding their brightness at low latitudes, where they merge into the radiation of the disk.

(*iii*) At low latitudes they lie roughly perpendicular to the galactic equator.

(*iv*) Quigley and Haslam (1965) have fitted the observations of three spurs to arcs of small circles of quite large radius. For some parts the fit is good, e.g. for the northern edge of the North Galactic Spur, whilst for the fainter parts of the spurs there is considerable uncertainty.

(*v*) The North Galactic Spur has a very sharply defined northern edge, and to the south there are narrow ridges of emission running roughly parallel to it. The other spurs do not seem to contain structure of an angular scale much less than 2°.

(*vi*) The North Galactic Spur is strongly polarized at high frequencies.

Several *explanations* have been put forward to account for the spurs. Those currently considered are:

(1) The spurs are old supernova remnants, comparable to the Cygnus Loop but much closer to the Sun, at distances of some 20 pc. (Hanbury Brown *et al.* 1960)

(2) The cosmic-ray pressure in the disk leads to instabilities in the magnetic field, and loops of field may be blown out to large values of z, appearing as long fingers roughly perpendicular to the galactic plane. (Parker 1965)

(3) The interpretation of the spurs as three separate loops is incorrect. The separate parts may be joined into a single feature corresponding to a helical tube of magnetic field wrapped round the local spiral arm. (Rougoor 1966)

(4) The spurs are very-large-scale features of the galactic halo.

No strong arguments have been put forward in favour of any one of these theories. Alignment of magnetic fields along the spurs and consequent polarization of the radio emission might be expected in all models. The supernova theory has been most strongly supported, but three arguments suggest that it may not be correct:

(*a*) The alignment of the spurs perpendicular to the galactic plane is not explained.

(*b*) The probability of having three supernova remnants so close to the Sun is very small.

(*c*) Bingham (1967) has found a correlation between the direction of the magnetic field in the North Galactic Spur derived from radio polarization measures and that derived from optical polarization measures of stars (Behr 1959). The correlation exists only for stars whose distances exceed 120 pc; this implies that the Spur is at roughly this distance. It would then be quite unlike any supernova remnant of which we know.

4. THE HALO

In recent years there has been little progress in studies of the radio halo of the Galaxy. This is scarcely surprising, since improvements in resolving power will not necessarily change radically our view of a feature which fills the whole sky.

The *observational facts* which model haloes of the kind originally discussed by Šklovskij (1952), Baldwin (1955) and Mills (1959) set out to explain were:

(*i*) At high galactic latitudes ($|b| \gtrsim 40°$), where the disk radiation is very weak, comparatively high brightness temperatures were observed.

(*ii*) This emission was considerably more intense at longitudes towards the galactic centre than towards the anticentre.

The observed ratio of brightness temperatures for longitudes 0° and 180° at $b = +45°$ was about 3 : 1, and it was roughly the same at corresponding southern latitudes. If we assume all of the radiation to be galactic in origin and take a modern distance from the Sun to the galactic centre of 10 kpc, this ratio gives a radius for a homogeneous spherical halo of about 16 kpc. Some of the radiation at high latitudes must however arise from extragalactic sources, and the true radius would be somewhat less than this value. The *emission per unit volume* in this model is approximately $1{\cdot}8 \times 10^9$ W Hz^{-1} pc^{-3} = $0{\cdot}6 \times 10^{-39}$ erg sec^{-1} Hz^{-1} cm^{-3} at frequencies of 80–85 MHz, and would be $0{\cdot}6 \times 10^9$ W Hz^{-1} pc^{-3} at 400 MHz, considering the spectral variation. This is approximately 1/20 of the emission per unit volume in the disk which was discussed in Section 1.

This simple picture was upset by our later knowledge of the *spurs*, which are probably local foreground objects. The status of the radio halo now depends on two pieces of observational evidence:

(*i*) the relative brightness temperatures at the four points $l = 180°$, $b = \pm 45°$ and $l = 0°$, $b = \pm 45°$;

(*ii*) an estimate whether these temperatures are significantly affected by the presence of spurs or other irregular features.

It is useful to relate the measured ratio of temperatures at $l = 0°$ and $l = 180°$ to the radius of a homogeneous spherical model halo for two cases:

(*a*) the extragalactic radiation is zero;

(*b*) the extragalactic radiation contributes one third of the minimum sky brightness for frequencies near 100 MHz. (This is the best value obtained so far from work on the galactic radio spectrum.)

The *temperature ratios and corresponding radii* are given in Table 1. The point at $l = 0°$, $b = +45°$ lies inside the arc of the North Galactic Spur, and several authors have supposed that the brightness temperatures inside the whole area enclosed by the arc are higher than they would be if it were absent. There is no clear way of ascertaining whether this is so. A reasonable guess at the contribution from Spur radiation reduces the ratio of brightness temperatures at $l = 0°$ and $l = 180°$ to about 2:1.

Table 1

Brightness distribution for homogeneous spherical haloes of various sizes

Brightness temperature ratio $(l = 0°, b = \pm 45°)/(l = 180°, b = \pm 45°)$	Radius (kpc) Case (*a*)	Case (*b*)
3·0	16	14
2·5	18	15
2·0	22	18
1·5	35	25

Southern galactic latitudes have been less intensively observed. The only recent survey to cover this region with adequate sensitivity at high latitudes is that of Mathewson *et al.* (1965) at 30 MHz. The ratio of brightness temperatures for $l = 0°$, $b = -45°$ and $l = 180°$, $b = -45°$ is again approximately 2:1, and there is no evidence to suggest that this ratio is seriously affected by the presence of spurs.

A ratio of 2:1 as suggested by these observations indicates a radius for the halo of about 22 kpc (or 18 kpc after allowing for an extragalactic contribution) and an emission per unit volume of only 1/40 that of the disk. Unfortunately even the observational situation is not clear, since observations by Burke (Paper 59 in this volume) indicate that the true ratio of brightness temperatures at southern latitudes is nearer 1:1. If this should prove to be correct, the most important evidence for the existence of the radio halo would disappear. This observational discrepancy is in urgent need of settlement one way or the other. A compromise in which the temperature ratio becomes 1·5:1 would be very unsatisfactory, as it would indicate a halo having a very large radius of some 35 kpc, and this would seem impossible to substantiate with certainty.

At present it seems that a brightness temperature ratio of 2:1 and a radius of 18 kpc for the halo are the most acceptable values. On this basis it is possible to deduce a little concerning the *shape of the halo* from plots of brightness temperature vs. latitude. In the northern sky $l = 70°$ is a convenient longitude for this, since it is free of spurs and since the disk radiation is here confined to very low latitudes. In Figure 2, the curve is a plot of temperatures from the 178-MHz survey of Turtle and Baldwin (1962); crosses mark temperatures for a spherical halo of radius 18 kpc. The close agreement indicates that the portion of the halo more than 10 kpc from the galactic centre is essentially spherical. Alternatively one may argue that the rather uniform temperatures at high latitudes point to the complete absence of a halo. In this case the extragalactic radiation would be very considerable.

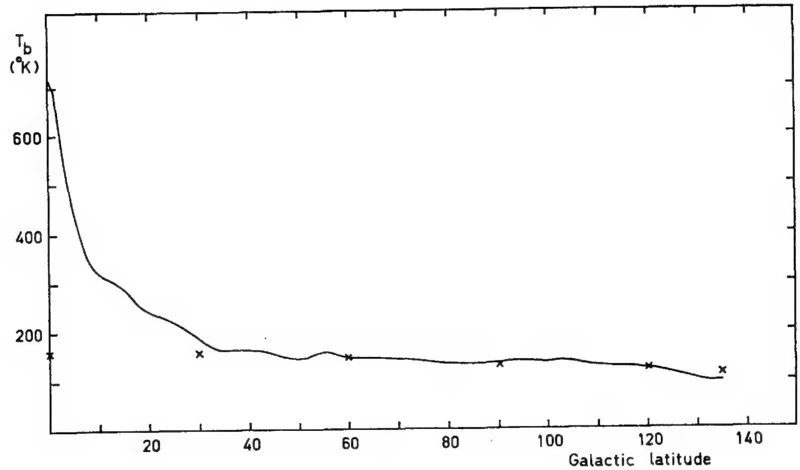

FIG. 2. Brightness temperature T_b at 178 MHz as a function of galactic latitude at longitude $l^{II} = 70°$. Crosses mark temperatures expected for a spherical halo of 18 kpc radius.

5. THE GALACTIC RADIO SPECTRUM

Our knowledge of the galactic radio spectrum has improved substantially over the last few years. Two rather separate problems can be distinguished.

a. The spectrum at low galactic latitudes

For studies at low latitudes, it is clearly essential to use high-resolution surveys. A number are now available, most of them calibrated by means of point sources. The analysis required in deducing the galactic radio spectrum is not straightforward, since the thermal radiation from ionized hydrogen and the non-thermal radiation are mixed at the lowest latitudes. The procedure has usually been to adopt a non-thermal spectrum from observations at reasonably low latitudes, and to use this at the lowest galactic latitudes to separate the thermal from the non-thermal radiation (Westerhout 1958, Large *et al.* 1961, Komesaroff 1961, Mathewson *et al.* 1962). This raises the question whether the spectrum of the non-thermal radiation changes with latitude. The justification for the procedure adopted follows from a comparison of the results with low-frequency measurements, where the ionized hydrogen appears in absorption. The agreement obtained seems to be satisfactory and the non-thermal *spectral index*, α, defined by $S \propto \nu^{-\alpha}$, with S = flux density and ν = frequency, is 0·6 ± 0·1. It is probable that, because of the ionized hydrogen, we shall never have a very good value of α at low latitudes.

b. Spectra at high latitudes and in the anticentre region

The second observational problem is that of determining the spectrum at high latitudes, and also close to the galactic equator in the region of the anticentre, where angular resolving power is less important. The most accurate measurements have been made with aerials geometrically scaled at different frequencies. The observations demonstrate clearly

that the spectrum of the *total* background at high latitudes varies over the sky. Contours of the mean temperature spectral index β ($\beta = \alpha + 2$) between 17·5 and 81·5 MHz are shown in Figure 3 (Bridle 1967). The contours of spectral index follow closely those of absolute brightness; the high value of β near 09^h30^m, $+35°$ occurs in the region of minimum brightness, and low values of β occur along the galactic ridge running from 22^h, $+55°$ to 05^h, $+35°$. Several workers (Turtle *et al.* 1962, Purton 1966, Yates and Wielebinski 1966) have found that there is a very good linear relation between temperatures at one frequency and those at another, but that the line does not pass through the zero of both temperature scales. This provides evidence for a galactic spectrum which is the same from point to point on the sky, superimposed on a *background of somewhat different spectral index* and it naturally accounts for the correlation between sky brightness and spectral index noted in Figure 3. This effect is to be expected, since the amount of extragalactic radiation derived by integration of the flux densities of known sources from the log N vs. log S curve down to the present limits of measurement represents roughly 1/6 of the minimum brightness of the sky at 178 MHz. The effect is therefore important,

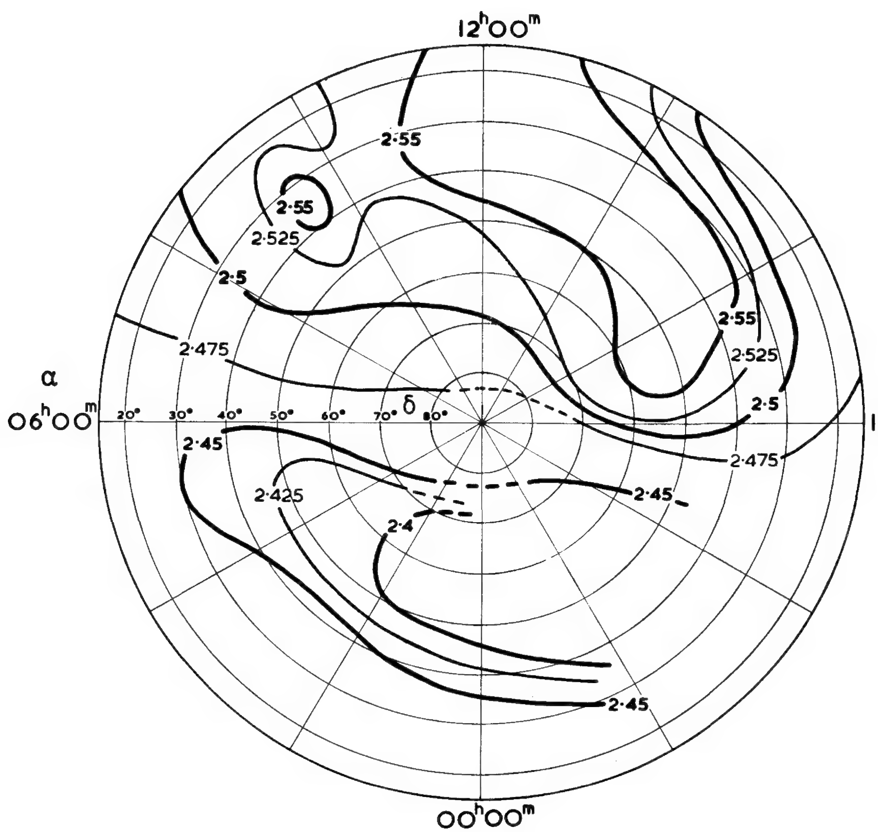

FIG. 3. Contours of temperature spectral index β between 17·5 and 81·5 MHz (Bridle 1967), plotted as function of right ascension and declination.

and later analysis suggests that the total extragalactic radiation is as much as 1/3 of the minimum brightness.

The extragalactic radiation is, by hypothesis, isotropic and hence one may separate the galactic radiation from it by plotting spectra of the differences in temperature between two points in the sky. I shall refer to such a radio spectrum as a *differential spectrum*, to distinguish it from the total spectrum at any one point in the sky. This approach is justified if one finds that the differential spectrum is the same over the whole sky. If this is not so, then we must argue about the usefulness of the technique. This kind of analysis has been made in both hemispheres, for observations with single dipoles above reflecting screens, and there is now a good measure of agreement. The results, at frequencies between 10 and 85 MHz, of Andrew (1966) in the northern hemisphere and Yates and Wielebinski (1966) in the southern, are plotted in Figure 4. Since the observations covered different regions of sky, an arbitrary scaling factor has been used to bring the intensities to a common basis; they are given relative to that at 38 MHz. The results agree within the limits of error and the brightness spectrum may be represented by a line of slope $-\alpha = -0{\cdot}45$.

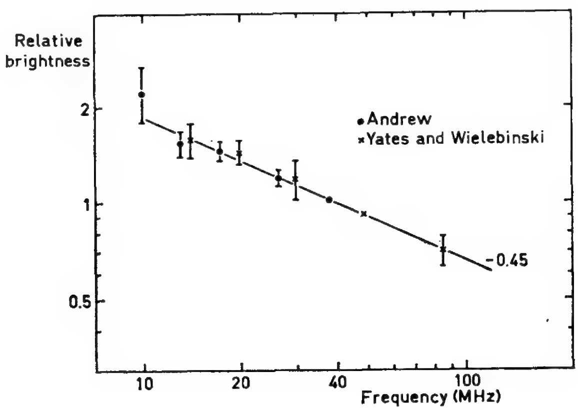

FIG. 4. Differential galactic spectrum from dipole measurements in the northern (Andrew 1966) and southern (Yates and Wielebinski 1966) hemispheres. Brightness given relative to that at 38 MHz. 'Differential' means: after elimination of the isotropic radiation.

At somewhat higher angular resolutions ($15^\circ \times 50^\circ$), the observations of Turtle *et al.* (1962) were extended and improved by Purton (1966). He found no differences between the differential radio spectra obtained in each of two regions of sky, corresponding roughly to the galactic plane at the anticentre and the halo at high latitudes. More recently Bridle (1967) has made observations with a resolution of $17^\circ \times 12^\circ$ at 17·5 and 81·5 MHz and, by dividing the sky into areas more closely related to the structural features of the Galaxy, has discovered small differences between the differential galactic spectra in two regions of sky. These regions were:

$$\text{Region 1}\begin{cases} +50^\circ > b > +15^\circ \\ 140^\circ < l < 220^\circ \end{cases} \qquad \text{Region 2}\begin{cases} b > 70^\circ & \text{for all } l \\ +70^\circ > b > +50^\circ & 50^\circ < l < 90^\circ \\ +50^\circ > b > +30^\circ & 70^\circ < l < 90^\circ \end{cases}$$

The first of these contains radiation from the local spiral arm, whilst avoiding low latitudes, where ionized hydrogen may play an important and confusing part. The second region covers directions which lie in the interarm region or at high latitudes. The two mean spectral indices, α, between 17·5 and 81·5 MHz are $0{\cdot}38 \pm 0{\cdot}03$ and $0{\cdot}47 \pm 0{\cdot}04$ for Regions 1 and 2 respectively. These values lie just outside their mutual error limits, and the difference is probably real.

By combining his results with those of Purton (1966) analysed in the same way, Bridle obtained the spectra illustrated in Figure 5. Both spectra show roughly constant values of α for frequencies between 13 and 100 MHz, but steepen quite sharply at about 200 MHz. The points at 610 MHz are preliminary measurements by Howell (private communication), which confirm the 404-MHz points which previously were the only ones showing a departure from a straight spectrum. The observations of Penzias and Wilson (1966) at 4080 MHz, giving a spectral index of about 0·9, also confirm the general *steepening* of the spectrum *toward high frequencies*.

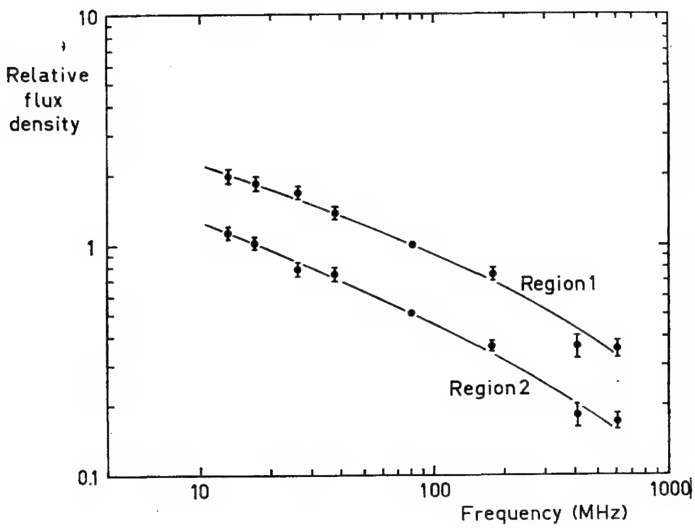

FIG. 5. Differential galactic spectra of Regions 1 and 2. The ordinate is flux density relative to that at 81·5 MHz; the curves for the two regions have been arbitrarily separated by a factor of two at 81·5 MHz (Bridle 1967).

The similarity of the spectra for Regions 1 and 2 presents serious problems. It is difficult to account for both spectra by the same flux of electrons moving in differing magnetic fields. So we are in trouble if we wish to associate one spectrum with the disk radiation and one with the halo radiation. The difficulties might be partially overcome, if the halo has a filamentary structure such that the strength of the magnetic field in the filaments is comparable to that in the disk but they only occupy a small fraction of the total volume.

c. Relation of the radio spectrum to the cosmic-ray electron spectrum

It is of great interest to compare the radio spectrum with the energy spectrum of the cosmic-ray electrons, which has now been measured over a wide range of energies. For a magnetic field of 10^{-5} gauss, the electrons radiating mainly at 100 MHz have energies of 1 GeV. The differential energy spectrum obtained by L'Heureux and Meyer (1965) in this region has an index $\gamma = 1{\cdot}6 \pm 0{\cdot}4$, corresponding to a radio spectral index $\alpha = \frac{1}{2}(\gamma - 1) = 0{\cdot}3 \pm 0{\cdot}2$, which is in reasonably good agreement with the radio observations. More recent evidence on the steepening of the cosmic-ray electron spectrum at higher energies agrees with the steepening of the radio spectrum toward high frequencies, but the line drawn through the radio data in Figure 5 has perhaps rather too sharp a bend near 200 MHz. It seems likely that estimates of the magnetic field from a comparison of these spectra may prove more accurate than the estimates based on the total intensity of the galactic radiation as discussed most recently by Felten (1966).

d. The spectrum of the Spur

There is now some evidence that the spectrum of the North Galactic Spur may differ considerably from that of the general background at high latitudes. A preliminary map made by Purton with the 10-MHz telescope of the Dominion Radio Astrophysical Observatory at Penticton (Canada) shows absorption patches along the ridge of the Spur, which probably are ionized-hydrogen regions. Low values of the spectral index of the spur between 17·5 and 81·5 MHz were also obtained by Bridle (1967). At higher frequencies, results obtained by Quigley and Haslam (private communication) and work at Cambridge suggest that the spectral index may increase to about 0·7. Further work is needed to establish these interesting new findings.

6. REMNANTS OF SUPERNOVAE

This subject is now much too large to be treated comprehensively in a review of this kind; it is only possible to mention briefly issues which have a direct bearing on the radio emission from the Galaxy as a whole. These are perhaps the most important aspects of supernovae but, unfortunately, we know very little about them. They can be best phrased as a series of questions awaiting reply.

a. What contribution do supernova remnants make to the total galactic background?

In Section 2, I have presented arguments to show that they provide only a small proportion of the total disk radiation, but there is not general agreement about this. Work by many authors has increased the number of known supernova remnants to about 25, but we have reliable distances for only 4. Their spatial density is thus still uncertain.

b. What contribution do supernovae make to the flux of cosmic-ray electrons in the Galaxy?

Observations of the cosmic-ray electrons in the energy range of direct relevance to radio astronomy (0·3 to 3·0 GeV) have shown their numbers to be greatly in excess of those expected for secondaries arising from collisions of cosmic-ray protons with the interstellar gas. Consequently, other sources of cosmic-ray electrons must now be more seriously considered. Several workers have demonstrated that the flux of electrons in

supernova remnants could plausibly supply the galactic flux, but there are a number of problems requiring solution before this assertion can be based on more than an order-of-magnitude calculation.

(*i*) *How are cosmic-ray electrons contained in supernova remnants?*

Studies of the structure of supernova remnants—see also subsection (*c*) below— are clearly important for this problem. Radio observations have shown that nearly all remnants (with the notable exception of the Crab Nebula) have a *shell structure*, the shell thickness varying from source to source. The shells probably indicate regions of strong magnetic field, but the structure of this field is not known. Observations by Gardner and Milne (1965) of the remnant of the supernova of A.D. 1006 have shown significant polarization of the radiation at 11 cm wavelength. This offers the hope that the broad features of the magnetic field may be understood in the near future.

(*ii*) *Do cosmic-ray electrons escape from supernova remnants?*

If so, do they do so continuously, or only at some late stage in the history of a remnant, when the symmetrical shell structure begins to break up into separate parts? The secular decrease in flux density of Cas A has been measured (Högbom and Shakeshaft 1961, Heeschen and Meredith 1961); comparison with a theoretical model of the expected decay (Šklovskij 1960) yields reasonable agreement. The main cause of the decrease lies in energy losses of the electrons, arising from the adiabatic expansion of the supernova remnant. Uncertainties in the change of magnetic-field strength with time, and concerning a possible acceleration of particles throughout the history of the remnant, make it unlikely that decreases in flux density due to escape of electrons will be detectable. In any case the rate must be small, since remnants having an age of some 10^5 years are known. An alternative method of detecting the escape of electrons from supernova remnants is to search for their emission in the interstellar magnetic field close to the supernova. In one case there may be evidence of this: in the map of Cas A at 1407 MHz by Ryle *et al.* (1965), there is weak emission outside the sharp edge of the shell, and at one position angle there is a flare of emission extending about 1′ (arc) beyond the edge.

(*iii*) *Do the cosmic-ray electrons in supernovae have the same energy spectrum as the galactic flux?*

We should not expect the spectra to be identical, since many physical processes may act on the electrons during their lifetime after escape from the supernova. The radio spectral indices of the young supernova remnants (Cas A 0·77, Kepler 0·60, Tycho Brahe 0·61, Crab 0·27) show no relation with the galactic radio spectrum, but for those few relatively *old* remnants whose spectra are well determined (Table 2) there seems to be a very close connection. The values of α listed in Table 2 lie very close to the mean spectral index for the Galaxy between 13 and 178 MHz, $\alpha = 0{\cdot}42$ (Section 5*b*). Two possible explanations of this close agreement are (1) that at this late stage in the evolution of a supernova remnant the particles are released into the interstellar medium, giving the observed spectrum, or alternatively (2) that the remaining filaments of strong magnetic field in the supernova remnants are illuminated by the flux of galactic electrons passing through them (Van der Laan 1962). If the field strength in supernova shells is large, then the curvature detectable in the galactic radio spectrum is shifted to much higher frequencies in supernovae and may well have escaped detection up to now.

Table 2

Spectral indices of old supernova remnants

Name of source	Spectral index, α
IC 443	$0{\cdot}41 \pm 0{\cdot}04$
Cygnus Loop	$0{\cdot}47 \pm 0{\cdot}10$
HB 9	$0{\cdot}45$
HB 21	$0{\cdot}4 \pm 0{\cdot}1$
W 44	$0{\cdot}40 \pm 0{\cdot}04$

(c) *The remnant of Tycho Brahe's Supernova*

It is clear from the above discussion that we have very little idea of the detailed processes governing the containment of cosmic-ray electrons in supernova shells. One new piece of evidence which may throw light on this problem comes from recent observations of the remnant of Tycho Brahe's Supernova with the one-mile radio telescope at Cambridge. Figure 6 shows the map obtained at 1407 MHz with beamwidths of 21″ (arc) in right ascension and 23″ (arc) in declination. The object has striking circular symmetry and appears to be the most suitable remnant for model-fitting yet found. It has a very sharp outer edge, unresolved by the beam in many places; a narrow bright ring of radio emission, lying just within the outer edge; and very low brightness temperatures in the centre, dropping effectively to zero in places. This latter feature is inconsistent with any spherical-shell model in which the emission is isotropic. It seems most probable that the magnetic field is aligned parallel to the surface of the shell, and that the electrons have an anisotropic velocity distribution, very few electrons having velocities making large angles with the field Baldwin (1967). Such effects have been suggested earlier for electrons moving in the interstellar magnetic field, but this is the first observational evidence for its occurrence in astronomical circumstances.

7. NORMAL GALAXIES

Observations of normal galaxies can help in two ways to further our knowledge of the Galaxy:

(*a*) features which we suspect may be present in the continuum radiation in our own Galaxy (e.g. the halo and spiral arms) may be more readily detected in objects seen from outside than in the Galaxy, where our viewpoint is inconvenient for many purposes;

(*b*) only by comparisons with other galaxies can we establish in what respects the Galaxy is 'normal'.

(*a*) Many early observations of M 31 indicated a large extension of the radio object, beyond the limits of the optical disk, and gave support to the idea of a *radio halo* in the Galaxy. Later Mathewson and Rome (1963), from observations at 408 and 1400 MHz, found that several Sc galaxies do not possess radio haloes and that the source of emission is considerably smaller than the optical disk. Observations by De Jong (1965, 1966) at 750 and 1415 MHz confirmed this, except in the case of M 31 which he found to be extended. At a lower frequency (408 MHz) Mills and Glanfield (1965) showed that the radio sources appeared to be coextensive with the optical objects. Thus observations of

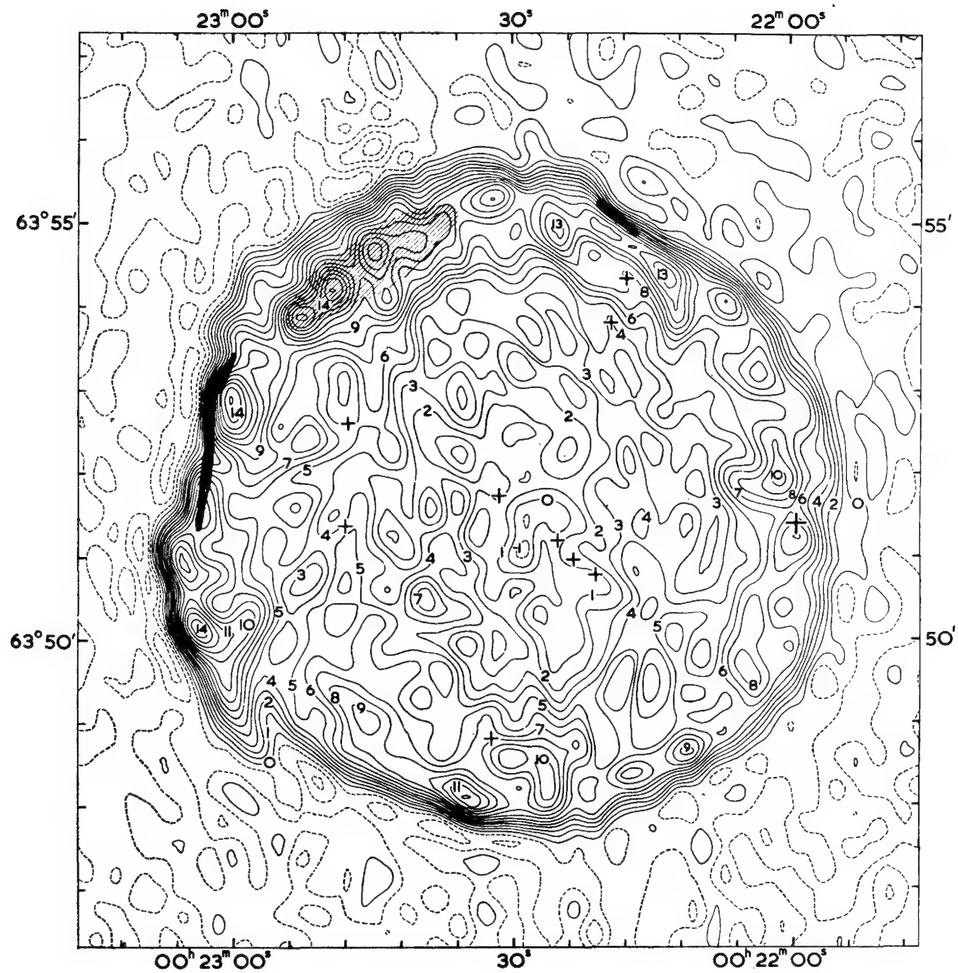

FIG. 6. Remnant of Tycho Brahe's Supernova, as observed at 1407 MHz with the one-mile radio telescope at Cambridge.

other galaxies do not provide clear-cut evidence on the problem of the existence of a halo in the Galaxy.

No clear indication for *spiral arms* in the continuum radiation of M31 has been found so far.

(*b*) The most complete survey of *normal galaxies* down to specific limits of magnitude and flux density is that by Heeschen and Wade (1964). From their results, and allowing for the spectral variations between 400 MHz and their observing frequencies of 750 and 1400 MHz, one may derive the intrinsic *radio luminosities* of the galaxies. These lie in the range (0·3 to 20) $\times 10^{21}$ W Hz^{-1} sr^{-1} at 400 MHz; considerable numbers of galaxies,

which were too weak to be detected, fall below the lower limit of this range. The emission from the disk of the Galaxy, derived from the figures given in Section 1 of this review, is approximately $0{\cdot}2 \times 10^{21}$ W Hz^{-1} sr^{-1}, making our Galaxy a rather weak source if the halo is non-existent. The emission from the halo following from the most likely figures given in Section 4 lies in the range ($0{\cdot}5$ to $1{\cdot}0$) $\times 10^{21}$ W Hz^{-1} sr^{-1}, yielding a total emission from the Galaxy of ($1{\cdot}0 \pm 0{\cdot}3$) $\times 10^{21}$ W Hz^{-1} sr^{-1}.

The *radio spectra* of normal galaxies are at present very poorly determined; only for M31 do we have a good value. The spectral index of $0{\cdot}53 \pm 0{\cdot}07$ (Kenderdine and Baldwin 1965) over the frequency range 38 to 1400 MHz is in close agreement with that for the Galaxy of 0·56 between 38 and 610 MHz.

8. OBSERVATIONAL NEEDS

Several problems noted in this survey need urgent attention from observers. Those which I believe to be most important are listed below.

(*a*) A survey of good sensitivity and moderate resolution at high latitudes in the southern hemisphere. This should provide much valuable information on the structure of the spurs, and may lead to a conclusion regarding the existence of the galactic halo.

(*b*) High-resolution surveys in which the beam efficiency and the distribution of side-lobes over the sky are known in some detail. These are essential requirements if the observations are to be used for accurate spectral work.

(*c*) More detailed maps of a few normal galaxies.

The first, at least, does not involve great advances in technique, and should be relatively easy to accomplish with existing instruments. The others are, I hope, a challenge to observers' skill.

REFERENCES

Andrew, B. H. 1966, *Mon. Not. R. astr. Soc.*, **132**, 79.
Baldwin, J. E. 1955, *Mon. Not. R. astr. Soc.*, **115**, 690.
Baldwin, J. E. 1967, in preparation.
Behr, A. 1959, *Veröff. Univ. Sternw. Göttingen*, **7**, 199 (No. 126).
Bingham, R. G. 1967, in preparation.
Bridle, A. H. 1967, *Mon. Not. R. astr. Soc.*, **136**, 219.
Burton, W. B. 1966, *Bull. astr. Inst. Netherl.*, **18**, 247.
Davies, R. D., Hazard, C. 1962, *Mon. Not. R. astr. Soc.*, **124**, 147.
De Jong, M. L. 1965, *Astrophys. J.*, **142**, 1333.
De Jong, M. L. 1966, *Astrophys. J.*, **144**, 553.
Felten, J. E. 1966, *Astrophys. J.*, **145**, 589.
Gardner, F. F., Milne, D. K. 1965, *Astr. J.*, **70**, 754.
Hanbury Brown, R., Davies, R. D., Hazard, C. 1960, *Observatory*, **80**, 191.
Heeschen, D. S., Meredith, B. L. 1961, *Nature*, **190**, 705.
Heeschen, D. S., Wade, C. M. 1964, *Astr. J.*, **69**, 277.
Högbom, J. A., Shakeshaft, J. R. 1961, *Nature*, **189**, 561.
Hornby, J. M. 1966, *Mon. Not. R. astr. Soc.*, **133**, 213.
Hoyle, F., Ireland, J. G. 1961, *Mon. Not. R. astr. Soc.*, **122**, 35.
Kenderdine, S., Baldwin, J. E. 1965, *Observatory*, **85**, 24.
Komesaroff, M. M. 1961, *Austr. J. Phys.*, **14**, 515.
Komesaroff, M. M. 1966, *Austr. J. Phys.*, **19**, 75.

Large, M. I., Mathewson, D. S., Haslam, C. G. T. 1961, *Mon. Not. R. astr. Soc.*, **123**, 113.
Large, M. I., Quigley, M. J. S., Haslam, C. G. T. 1962, *Mon. Not. R. astr. Soc.*, **124**, 405.
L'Heureux, J., Meyer, P. 1965, *Phys. Rev. Lett.*, **15**, 93.
Mathewson, D. S., Rome, J. M. 1963, *Observatory*, **83**, 20.
Mathewson, D. S., Healey, J. R., Rome, J. M. 1962, *Austr. J. Phys.*, **15**, 354.
Mathewson, D. S., Broten, N. W., Cole, D. J. 1965, *Austr. J. Phys.*, **18**, 665.
Mills B. Y. 1959, IAU Symposium, no. 9, *Paris Symposium on Radio Astronomy*, Ed. R. N. Bracewell, p. 431, Stanford Univ. Press, Stanford.
Mills, B. Y., Glanfield, J. R. 1965, *Nature*, **208**, 10.
Parker, E. N. 1965, *Astrophys. J.*, **142**, 584.
Pauliny-Toth, I. I. K., Shakeshaft, J. R. 1962, *Mon. Not. R. astr. Soc.*, **124**, 61.
Penzias, A. A., Wilson, R. W. 1966, *Astrophys. J.*, **146**, 666.
Purton, C. R. 1966, *Mon. Not. R. astr. Soc.*, **133**, 463.
Quigley, M. J. S., Haslam, C. G. T. 1965, *Nature*, **208**, 741.
Rougoor, G. W. 1966, *Astrophys. J.*, **144**, 852.
Ryle, M., Elsmore, B., Neville, A. C. 1965, *Nature*, **205**, 1259.
Seeger, C. L., Westerhout, G., Conway, R. G., Hoekema, T. 1965, *Bull. astr. Inst. Netherl.*, **18**, 11.
Šklovskij, I. S. 1952, *Dokl. Akad. Nauk SSSR*, **85**, 1231.
Šklovskij, I. S. 1960, *Astr. Zu.*, **37**, 256 (translation in: 1960, *Soviet Astr.*, **4**, 243).
Turtle, A. J., Baldwin, J. E. 1962, *Mon. Not. R. astr. Soc.*, **124**, 459.
Turtle, A. J., Pugh, J. F., Kenderdine, S., Pauliny-Toth, I. I. K., 1962, *Mon. Not. R. astr. Soc.*, **124**, 297.
Van der Laan, H. 1962, *Mon. Not. R. astr. Soc.*, **124**, 125.
Westerhout, G. 1958, *Bull. astr. Inst. Netherl.*, **14**, 215.
Yates, K. W., Wielebinski, R. 1966, *Austr. J. Phys.*, **19**, 389.

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57. STRUCTURE IN THE RADIATION OF THE GALACTIC DISK

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ABSTRACT

Observations at various frequencies between 136 and 1400 MHz indicate a considerable amount of structure in the galactic disk. This result appears consistent both with measured polarization percentages and with considerations of the strength of the galactic magnetic field.

I wish to draw attention to the irregular nature of the radiation of the galactic disk. Davies and Hazard (1962) emphasized this lumpiness of the disk emission in their discussion of a survey of a region near the anticentre, extending from $l^{II} = 186°$ to $210°$ and from $b^{II} = -15°$ to $+15°$. They found that in this region about half the disk emission appeared in this lumpy component; the same fraction was obtained on the equator and at $|b^{II}| \approx 15°$. Observed sizes of irregularity ranged from regions comparable with the beamwidth to regions 10° in extent. A number of features were associated with faint filamentary nebulosities, which were probably the remnants of supernovae.

E. R. Hill and I have extended the survey of this region of the sky with new observations at Parkes. We mapped the area $l^{II} = 200°$ to $260°$, $b^{II} = -15°$ to $+15°$ at 136 and 408 MHz, and also took observations at 1400 MHz on an incomplete grid. This survey supported the conclusion of Davies and Hazard (1962) that about 50% of the disk component is lumpy, and composed of extended and apparently isolated regions of emission. Most of the more intense features, like those found in the previous survey, had a non-thermal spectrum consistent with a synchrotron origin of the radiation.

The high-resolution maps published recently by the Cambridge observers for 178 MHz and by the Ohio State Radio Observatory for 600 MHz show similar structure in the disk radiation.

The observed irregularity in the emission near the plane is what may be expected from a significant contribution by supernovae. Some compact sources will be associated with recent supernovae; in addition there will be a much larger contribution by weak extended sources, associated with supernovae of ages ranging up to 10^5 or perhaps 10^6 years.

Polarization measurements of the galactic background at the highest frequency so far investigated (1400 MHz) indicate about 10% polarization (see Van de Hulst, Paper 64). This should be compared with the 70% polarization expected for an individual region of synchrotron emission in an aligned magnetic field. The difference can be attributed partly to the effects of Faraday rotation near the galactic plane, and partly also to the superposition within the beam of emission from different regions, with different magnetic-field orientations. The magnetic fields in the shells of old supernovae will not necessarily be parallel to the general galactic magnetic field, although there may conceivably be a tendency for them to become so oriented at the final stages of deceleration.

Another subject relevant to this discussion is the magnetic-field strength B calculated from observations of the intensity of synchrotron emission, and from the Faraday rotation of extragalactic sources. The synchrotron-emission data give 12×10^{-6} gauss for the total field intensity, whereas the Faraday-rotation data (Paper 67) indicate 5×10^{-6} gauss for the net flux of the field. These values appear significantly different, in the sense expected for a tangled or looped structure in some of the magnetic field. The irregularities in the synchrotron emission would result from a certain amount of clumpiness in the field. Also, the field strength derived from synchrotron-emission data will be greater than the mean field strength, because the emission intensity is proportional to $B^{1.6}$.

REFERENCE

Davies, R. D., Hazard, C. 1962, *Mon. Not. R. astr. Soc.*, **124**, 147.

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58. DUAL-BEAM OBSERVATIONS AT 1417 MHz OF THE REGION OF THE NORTH POLAR SPUR

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ABSTRACT

This is a preliminary report of a survey carried out with a dual-feed system, which measures the intensity *gradient* along a path in the sky swept by the motion of the telescope. The accuracy reached is 0·04 °K of antenna temperature per 2° beam separation.

Using the Jodrell Bank telescope at 240 MHz, Large *et al.* (1966) have found several sharp features in the North Polar Spur. Recent observations with the Dwingeloo telescope at 1417 MHz, in an area extending from 10^h20^m to 18^h20^m in right ascension and from 0° to + 20° in declination, have confirmed and extended these findings.

We measure the intensity gradient along a path defined by the sweep motion of the telescope, by using a dual-feed system with a synchronous detector. Features much wider than the beam separation of 2° are effectively suppressed, whereas ridges having a width of the same order as the beam separation stand out clearly.

The observations are distinctly more difficult to interpret than measurements of total intensity, since the measured gradient depends on the sweep path of the telescope. In particular, structure running parallel to the sweep path will be missed. On the other hand, for the ridges which can be seen, the peak can be located accurately from the positions of zero gradient, and some information on possible asymmetry of the ridge cross-section can be obtained from a comparison of the positive and negative gradients.

The use of the dual-beam method together with sweeping in azimuth has led to an accuracy considerably better than 0·1 °K of antenna temperature difference per beam separation (0·2 °K of brightness temperature).

Figure 1 shows a sample of our results. The North Polar Spur can be followed quite easily from the galactic plane through its peak latitude of + 75° down to $b = +62°$, where it runs off the map at $\alpha = 12^h20^m$, $\delta = 0°$. There appears to be a link between the two ridges found in this region by Large *et al.* (1966).

We find that we generally can follow the other ridges in the region of the Spur over a larger distance than was possible in the Jodrell Bank observations. The reality of these ridges is fairly certain, as the zero-gradient points, which were determined without reference to neighbouring scans, form virtually continuous features on the contour map.

The observations, which were obtained during a survey for discrete extragalactic sources, give a root-mean-square gradient of 0·043 °K of antenna temperature per 2° beam separation in regions far from the North Polar Spur and from the galactic plane.

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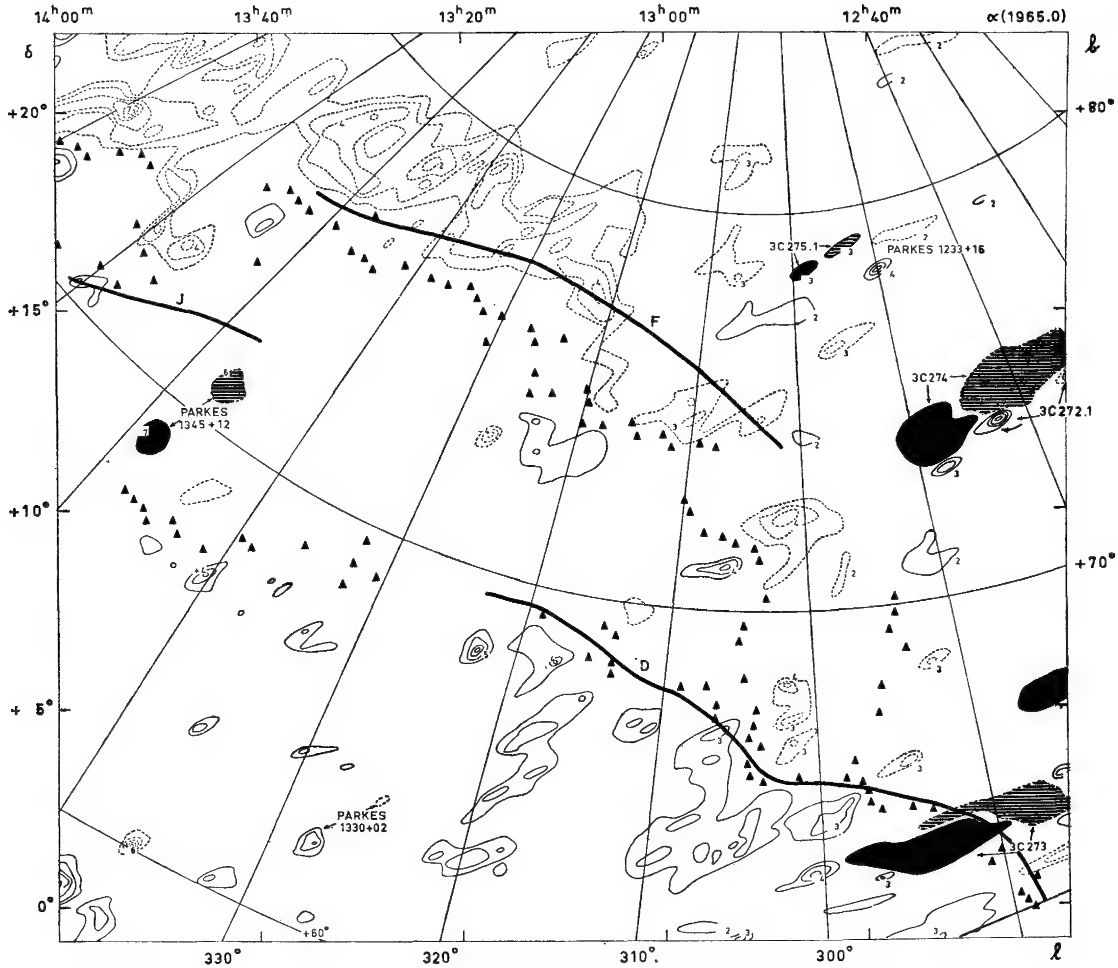

FIG. 1. Contour diagram of the high-latitude part of the North Polar Spur. The frequency of observation is 1417 MHz, the beam-width 0°.6. The scan direction is from upper right to lower left, and the spacing between two adjoining scans is $2^{m}.5$ in right ascension. The dashed contours correspond to a positive gradient in the scan direction, the solid contours to a negative gradient. One contour interval equals 0·058 °K of antenna temperature difference per 2° beam separation; the contours −1, 0 and +1 are not included as they were strongly affected by noise. For all strong features (steep gradients) the inner contours are omitted: the area of the feature is hatched for positive gradients and filled in for negative gradients. The peak values of the gradients are marked, except for those sources that were off-scale on the records. The known discrete sources are identified with a source number from either the 3CR or the Parkes catalogue. Points where the intensity gradient changes from a positive to a negative value, corresponding to ridge peaks, are indicated by triangles. For comparison the ridges in this area listed by Large *et al.* (1966) are indicated by heavy lines.

This residual gradient is a factor of three larger than can be explained by confusion due to weak extragalactic sources; it is probably galactic in origin.

A more complete report of this investigation is in press (1967).

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REFERENCES

Large, M. I., Quigley, M. J. S., Haslam, C. G. T. 1966, *Mon. Not. R. astr. Soc.*, **131**, 335.

Merkelijn, J. K., Davis, M. M. 1967, *Bull. astr. Inst. Netherl.*, **19**, no. 4, in press.

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59. UPPER LIMITS ON THE GALACTIC HALO AT 234 MHz

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ABSTRACT

Preliminary analysis of a survey at galactic latitudes −20°, −30°, and −40° indicates an upper limit of 30° K (antenna temperature) for the halo.

In collaboration with K. C. Turner, I have made a survey of the entire sky accessible to the 300-foot (91-m) transit telescope of the National Radio Astronomy Observatory (Green Bank, West Virginia, U.S.A.), at a frequency of 234 MHz ($\lambda = 1{\cdot}3$ m). The beamwidth to half-power points was 1°. The results presented here stem from a preliminary reduction of part of the data, covering the declination range 0° to + 40°. The survey is at nearly the same frequency as that carried out at Jodrell Bank (240 MHz). It was intended primarily to investigate the large-scale structure of the galactic radio emission, and in particular to examine the question of the galactic halo.

It is important to define what one means by a galactic halo. In this case I shall mean a more or less spheroidal distribution of radio noise about the Galaxy. We particularly wished to compare our model with that of Mills (1959), which was based on observations at 85 MHz ($\lambda = 3{\cdot}5$ m), obtained with equipment of very different form. Our maps show the well-known features such as the galactic disk and the North Polar Spur very clearly, and we have placed emphasis on separation of disk and halo components. The spur structures, and the North Polar Spur in particular, distort the background markedly, and in order to avoid extrapolating through the spurs, we had to use only data from the southern galactic hemisphere. For a simple model, we have taken a uniform sphere of emission, with the Sun at the edge; this has the simple property that a plot of antenna temperature vs. longitude at constant latitude (to be precise, T_a vs. cos l) should appear as a straight line. The observed antenna temperatures, averaged over 5° × 5° squares, are shown in Figure 1, for galactic latitudes − 20°, − 30°, and − 40°. The run of T_a with cos l is remarkably similar for all three latitudes, and a least-squares fit of a straight line to the data yields a contribution of 30° from our model halo along a galactic diameter. This should be considered an upper limit, since the scatter of points about the least-squares line is large, and a line T_a = constant, implying no halo, fits the data almost as well.

The halo derived by Mills (1959) is not quite the same, but his axial ratio of 1·5 : 1 is not radically different from our spherical model, and a comparison of the two results implies that either the surface brightness varies with frequency ν as $\nu^{-2{\cdot}5}$ (so that $T_b \propto \nu^{-4{\cdot}5}$), or else different interpretations of the two surveys are necessary. Our conclusion

*The observations were made while the author was at the Department of Terrestrial Magnetism, Carnegie Institution of Washington, Washington, D.C., U.S.A.

is that a spheroidal halo is not required by our data, although an irregular halo, composed of large-scale spurs, cannot be excluded until we have a distance measurement of the North Polar Spur.

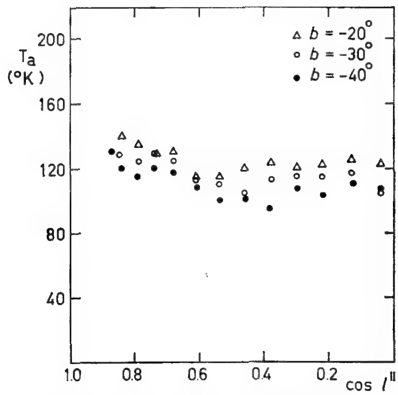

FIG. 1. Surface brightness of the Galaxy at 234 MHz, expressed in terms of antenna temperature T_a, and plotted against galactic longitude (in terms of cos l^{II}) to show the weakness of the halo component.

REFERENCE

Mills, B. Y. 1959, IAU Symposium, no. 9, *Paris Symposium on Radio Astronomy*, Ed. R. N. Bracewell, p. 431, Stanford University Press, Stanford, California.

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60. HALOES OF GALAXIES

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ABSTRACT

Observations of 25 galaxies with a 1′5 fan beam at 408 MHz allow coronas of about the size of the optical object; no large haloes have been found.

My comments refer to the large-scale structure in the non-thermal radiation. In dealing with such an irregular distribution as has been presented to us in Baldwin's review (Paper 56), there are semantic difficulties. I tend to regard the halo or corona as defined by the emission located more than about 1 kpc above the galactic plane. In my earlier analysis (Mills 1959), I used the high-latitude distribution to define such a corona which I assumed also to permeate the galactic plane, so that it included much of the disk component of others.

To establish mean parameters of such an irregular distribution, it is necessary to observe all around the centre of symmetry. Unfortunately no new southern-hemisphere observations at moderate frequencies and with good resolution are available. The old observations suggest a small corona, which has begun to break up at about the solar distance. In principle there need be no direct conflict with Burke's results (Paper 59), because his observations over a limited region are not necessarily representative. However, I suspect a real discordance.

When observed face-on at extragalactic distances, on the above model the Milky Way should show radio emission over most of the optical image. When observed edge-on, the thickness of the radio emission should be about half the length of the optical image. It is therefore interesting to compare results on other bright spirals. We have looked at more than 100 of the brightest southern galaxies at 408 MHz ($\lambda = 74$ cm), with the 1′5 fan beam of the east-west arm of the Molonglo Cross. To date results are available on only 25 spiral galaxies. Seven of these could not be observed because of confusion. None of the remaining 18 show evidence of a very large halo like that postulated for M 31, but all are consistent with the picture suggested above. Unfortunately none were lined up edge-on and north-south, so that the thickness of the distribution could not be measured directly. Four of the galaxies show clear evidence of a strong nuclear source.

REFERENCE

Mills, B. Y. 1959, IAU Symposium, no. 9, *Paris Symposium on Radio Astronomy*, Ed. R. N. Bracewell, p. 431, Stanford Univ. Press, Stanford.

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61. PHYSICAL HALO AND RADIO HALO

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ABSTRACT

A distinction is necessary between two concepts: the physical halo, forming a transition between the gas in the galactic disk and that in intergalactic space, and the radio halo, a spherical component (with $R \sim 15$ kpc) in the distribution of non-thermal radio emission.

There are two kinds of halo: physical halo and radio halo. The confusion in views which one meets in the discussion of the halo problem is often connected with a mix-up of these two concepts of the halo. But it is only a misunderstanding.

In the optical disk of our Galaxy the magnetic field strengths $H \sim 10^{-5}$ gauss, the gas density $\rho_{gas} \sim 10^{-24}$ g cm^{-3}, and half the layer thickness of the gas is $h_d \sim 100$ pc. In intergalactic space (within the boundaries of the local group) probably $H \sim 10^{-7}$ to 10^{-8} gauss and $\rho \sim 10^{-28}$ g cm^{-3}. Now the problem is: how does the transition between these two regions look? The existence of a more or less sharp transition has *a priori* low probability. However, as far as I know, before 1952 this question either was not discussed, or it was assumed that the transition is rather sharp and takes place immediately above the optical disk, i.e., at $z \sim 100$ pc. In 1952, Pikel'ner suggested that the transition mentioned must be a gradual one, and he introduced the concept of the halo. The statement that such a (physical) halo does exist means that something with $\rho \gg 10^{-28}$ g cm^{-3} and $H \gg 10^{-7 \text{ to } -8}$ gauss is present for $z \gtrsim 1$ kpc. It seems to me that this picture of a *physical halo* is fully confirmed and can be regarded as proved. Baldwin has shown (Paper 56, Section 1) that half the thickness of the radio disk is already of the order of 400 pc (the full equivalent thickness of the disk is 800 pc). It seems that there are no sharp boundaries here, so the existence of a halo with $H \gtrsim 10^{-6}$ gauss for 1 kpc $\gtrsim z \gg h_d \sim 100$ pc is established. Theoretical arguments accounting for the influence of cosmic rays indicate that there are haloes with $z \sim 10$ kpc.

Immediately after the introduction of the concept of physical halo, some authors claimed that there also exists a radio halo. By *radio halo* we mean a quasi-spherical body, with a radius R of 10 to 15 kpc, which can be observed at metre wavelengths ($T_b \sim 100$°K for $\nu = 180$ MHz, $\lambda = 1{\cdot}7$ m). Only the existence of such a radio halo seems to be open to discussion at present. Calculations made by several authors, particularly by Syrovatskij and by myself, show that the existence of a radio halo can be explained if we choose the following parameters: $H_{halo} \sim 3 \times 10^{-6}$ gauss, $R \sim 15$ kpc, and a concentration of relativistic electrons equal to that observed near the Earth. For such parameters $T_b \sim 100$ °K in the direction of the galactic poles for $\nu = 180$ MHz. The intensity is proportional to $H^{(\gamma+1)/2}$, and for $\gamma \approx 2$ taking $H \sim 10^{-6}$ gauss already suffices to make $T_b \sim 20$ °K. Such values of H and T_b are, of course, quite consistent with all existing data,

because, when people speak about the absence of a radio halo, they mean something like: $T_b \lesssim 20$ or 30 °K.

As I have said before, the question about the existence of a radio halo is strictly speaking open. However, it seems to me that there are some arguments in favour of the interpretation of the observed spherical component of the radio continuum distribution ($T_b \sim 100$ °K for $\nu = 180$ MHz) as a radio halo. Here I shall mention only that the alternative explanation attributes this spherical contribution to some new, metagalactic component of the radio emission. Although such a metagalactic component may exist, it requires a new, independent hypothesis for which I do not know any other ground. Besides it seems that this new, metagalactic component would have a spectral index $\alpha \approx 0{\cdot}6$, and this is lower than the average value of α for extragalactic sources.

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62. SUPERNOVA REMNANTS

R. L. Minkowski

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The brightness distribution of the remnant of Tycho's Nova, which Baldwin has shown in Paper 56 (Figure 6), and the distance of 5000 pc determined by Menon and Williams (unpublished), establish beyond doubt a diameter of 10·8 pc and an average velocity of 13 300 km/sec. The initial velocity must have been higher. The light-curve leaves no doubt that Tycho's Nova of + 1572 was a supernova of type I; for this type velocities of expansion of 20 000 km/sec or more are indeed suggested by the appearance of the spectra around maximum. The faintness of the optical remnant is easily understood as a consequence of the temperature of the order of 10^{10} °K, which must reign behind a shock-front moving with a velocity of the order of 20 000 km/sec. Application of Sedov's similarity solution for a strong explosion gives a total initial energy of about 3×10^{51} erg. If one third of this was kinetic energy, the ejected mass was 0·25 solar masses.

The Crab Nebula is obviously different from the Tycho remnant, and cannot be the remnant of a supernova of type I. Actually, no other type of supernova was known when the interpretation of the Crab Nebula as a supernova remnant was established around 1938. In fact the scanty data on the supernova of + 1054, which is identified with the Crab Nebula, do not prove that it was of type I. They do not agree well with that assignment, but also do not rule it out entirely. The low velocity of expansion of the Crab Nebula, combined with the fact that the transverse expansion shows no sign of deceleration, has always contradicted the assignment to type I. This has been overlooked quite generally.

Cassiopeia A is most likely the remnant of a supernova of type II with unusually large ejected mass, such as the supernova of 1961 in NGC 4303, which Zwicky designates as type III. The interpretation as a rare variant of type II is in accord with the uniqueness of Cassiopeia A in other respects. The total initial energy was probably about 7×10^{51} erg.

No recent remnant of an average supernova of type II is known. The supernova of + 185 may be an example, but the data on that star are very scanty and inadequate. The remnant, the radio source MSH 14–63, has been found optically by Westerlund (1964), but there is no detailed information on this faint and difficult object.

REFERENCE

Westerlund, B. E. 1964, IAU Symposium, no. 20, *The Galaxy and the Magellanic Clouds*, Eds. F. J. Kerr and A. W. Rodgers, p. 114, Austr. Acad. Sci., Canberra.

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63. DISCUSSION ON NON-THERMAL RADIO RADIATION AND THE GALACTIC HALO*

1. THE STRUCTURE OF THE GALACTIC DISK

J. R. Shakeshaft: Davies (Paper 57) has pointed out evidence for fine structure in the radio emission in the anti-centre region. This indicates, he believes, that a considerable proportion of this emission is due to remnants of supernovae. Since the percentage polarization of this radiation is so high in certain directions, the magnetic fields in these remnants would have to be well-oriented and closely parallel to the galactic plane.

P. G. Mezger: B. Höglund has carried out unpublished high-resolution observations of a limited part of the non-thermal disk component, using the 300-foot (91-m) telescope of the National Radio Astronomy Observatory (Green Bank, West Virginia, U.S.A.) at 750 MHz with a half-power beamwidth of about 20′ (arc). He observed a 'strip of sky' between declinations $+ 39° 56'$ and $+ 40° 26'$. This strip intersects the galactic equator close to the anticentre. To separate sources from the unresolved background, he stacked the observed α-scans so that they coincided at $b^{II} = 0°$ and drew the lower envelope of all scans. The result obtained in this way may be summarized as follows:

(*i*) A relatively large proportion of the non-thermal disk component consists of individual sources of small apparent diameter.

(*ii*) The remaining 'unresolved background' shows a strong asymmetry with respect to the galactic plane. It might be only a question of higher angular resolution to resolve at least part of this component too.

These results were reported at the IAU General Assembly in Hamburg, 1964.

2. THE GALACTIC HALO, AND RELATED PROBLEMS

B. F. Burke: This is a comment for Ginzburg (cf. Paper 61). Although our data do not require a halo, our upper limits still permit a halo of radius approximately 10 kpc, magnetic field of 10^{-6} gauss, and a reasonable distribution of electron energies, provided these are mostly greater than 1 GeV.

H. M. Tovmasjan: In 1965 about 300 spiral galaxies were observed at 20 cm wavelength with the 210-foot (64-m) telescope at Parkes, N.S.W., Australia. The data on about 120 of these have been analyzed now, and 34 of them have measurable radio emission. The latter were also observed at 11 cm wavelength, with the Parkes telescope having a 7′ beam; and at 75 cm wavelength, with the new Mills Cross at Molonglo, N.S.W., which has a beamwidth in right ascension of 1 5 (arc). These observations showed that the radio emission entirely comes from the very nuclear regions of these 34 galaxies, and no halo is seen at all three wavelengths. The radio magnitudes of some of these galaxies are about 2 or 3 magnitudes brighter than those of normal galaxies, so that they partly fill the gap between normal and radio galaxies.

*In the Symposium programme, this Discussion overlapped that of papers 64–67; the latter is here recorded after the individual papers. I have considerably rearranged the present Discussion, to make it follow the order of Baldwin's Introductory Report (Paper 56).—*Editor.*

It is of interest that the radio power of the galaxies studied correlates closely with the optical appearance of their nuclear regions.

B. J. Robinson comments: I wonder whether there is a clear separation between the 'normal galaxies' and the 'radio galaxies'. The two classes are usually approached from very different standpoints; in large samples they might overlap. While haloes may not be a characteristic of the first group, they are frequently associated with the second.

V. L. Ginzburg remarks: Observations in the cm- or dm-region hardly will help us to solve the problem of the existence of the halo. Indeed, in the halo the field is weaker than near the disk, and the energy of the electrons is lower, if we adopt a picture in which electrons are ejected into the halo from the disk. In this situation the halo would be much more pronounced at metre-wavelengths, and it is quite possible that it would be unobservable at shorter wavelengths.

J. Lequeux: Kazès has observed a number of galaxies at rather low frequencies with the 300-m Arecibo radiotelescope on Porto Rico. Most of them look like point sources with the 10′ beam at 430 MHz (70 cm wavelength) and there is no evidence for any halo.

C. H. Costain: Ginzburg remarked that one should look for radio halo distributions at metre-wavelengths. Observations of M 31 carried out at Penticton (B.C., Canada) at a frequency of 22 MHz (13·5 m wavelength) clearly show the presence of emission at great distances from the disk of the galaxy. For this galaxy, at least, there can be no doubt as to the physical reality of some sort of halo distribution.

M. S. Roberts comments: We keep referring (cf. also Baldwin, Paper 56, Section 7*a*) to M 31 as the one galaxy which does have a halo; this conclusion is based on observations with relatively wide beams. I suggest that the observed extensive distribution of radiation about M 31 is merely a beam-smearing effect of the many discrete radio sources which have been found in the vicinity of M 31 with narrower beams. See, e.g., the Ohio State and Illinois observations of M 31 as well as De Jong's observations of other normal galaxies.

G. Westerhout: I take exception to Baldwin's remark (Paper 56, Section 4) that high resolution is not needed to study the halo. On the contrary, surveys such as his own at 38 MHz and the Dwingeloo one at 400 MHz (Seeger *et al.* 1965) show a wealth of details which defies any description in terms of smoothness. I doubt whether, after removal of all the little humps and bumps, with diameters from 2° to 10°, much background is left. Depending on what distance one would adopt, these details may have sizes ranging from fifty to several hundred parsecs. It would be highly interesting to see the individual spectra of these 'objects', and theorists should certainly take them into account. I understand that Ginzburg indeed needs a small-scale distribution of the magnetic field to keep things together.

I also wish to note that I find it foolish, to say the least, to quote background spectra based on absolute-flux work with beamwidths of the order of 90°, in particular at frequencies around 10 or 20 MHz. Any reasonable model calculations show that the influence on the brightness temperature of absorption by ionized bydrogen extends to quite high latitudes. Even the work by Bridle and Purton shows this influence. Obviously, it is very difficult to do absolute calibrations with narrow beams. Perhaps one should calibrate narrow-beam surveys with a wide-beam calibrator, using suitable smoothing

techniques. In any case, the wide-beam spectra should be treated with extreme caution at the lower frequencies, and will almost certainly give too low a spectral index.

J. E. Baldwin answers Westerhout: We should indeed like to have accurate galactic spectra with high angular resolution. Unhappily, almost no one who makes high-resolution maps measures his beam efficiency accurately or his distribution of sidelobes at all. Without this information attempts to measure spectra at high latitudes are fruitless and dangerously misleading. Measures using geometrically scaled telescopes can produce good results, but so far only with fairly low resolution.

Ginzburg: The magnetic field in the halo has probably originated as a result of instability and some kind of 'pushing' outward from the disk. Consequently, we may expect that the field in the halo consists of several loops, etc. and in any case is not quite ordered. The same conclusion we can reach from the analysis of the question of cosmic-ray storage in the Galaxy. In an ordered field, confinement is very difficult. According to this, from the very beginning (1953) I have assumed a picture in which the halo has a turbulent field, and cosmic rays are diffusing through the halo. For the effective mean free path (in this case it is something like the characteristic length for disarrangement of the magnetic field) we may use a value of the order of 100 pc. This value follows from the model of cosmic-ray storage as well as from data concerning the distance between clouds in the disk. At the same time, of course, the presence of a large-scale magnetic field component in the halo is not excluded. An analogous situation occurs in the disk, where large-scale and small-scale fields exist together.

A. Maxwell asks: Ginzburg (Paper 61) gave an intensity spectral index of 0·6 and Burke (Paper 59) of 2·5, is that so? Would you care to comment on this discrepancy, which is really very large?.

B. F. Burke answers Maxwell: We derived a brightness spectral index of 2·5 from a direct comparison of our 234-MHz observations with those of Mills at 85 MHz. A spectral index of 0·6, as extrapolated from Mills' old data, would have resulted in a halo contribution to the brightness far higher than what we observed. The statement that Ginzburg's 'physical halo' (Paper 61) is consistent with our data depends upon the 234-MHz observations only.

J. H. Oort: As Ginzburg has pointed out, a considerable part of the halo must consist of irregularities. It should be possible in the future to obtain a higher-resolution survey of the halo, in which all irregular features can be well outlined. Polarization measures at high frequencies should then help to obtain the structure of these features and to measure how much of the remaining radiation is galactic.

Baldwin has given arguments (Paper 56, Section 3) indicating that the 'spurs' are unlikely to be supernova remnants. The strongest argument appears to be that, if they would result from ordinary supernovae, they should be very near-by; there should then be so many of them over the entire disk that their integrated radiation would be much stronger than the observed brightness of the disk. Also, comparison between the polarization measures at different wavelengths shows clearly that the North Polar Spur protrudes considerably outside the layer of ionized hydrogen, and therefore cannot be within this layer.

Would it be quite impossible that this Spur represents a very-large-scale structure in the magnetic field, and is possibly situated at a distance comparable to that of the galactic centre?

3. THE GALACTIC RADIO SPECTRUM

G. L. Verschuur: My impression of the curved spectra shown by Baldwin (Paper 56, Figure 5) was that instead of two points, at 400 and 600 MHz, below a straight line of a particular slope, there appeared to be only one point, at 178 MHz, above a straight line of a different slope. Did Andrew not recently have something to say about the curvature of this spectrum?

Baldwin answers: Andrew's measurements (Paper 56, Figure 4) referred to frequencies less than 100 MHz, where there is no evidence for curvature of the galactic spectrum. At higher frequencies we believe the curvature is real. The point at 81·5 MHz cannot be moved, since it is the reference point with respect to which the other values are quoted. The errors on the 178-MHz point are quite small. I think a straight spectrum is inconsistent with present data.

4. SUPERNOVA REMNANTS

T. K. Menon: I wish to discuss briefly the spectra of supernova remnants, and emphasize certain features which are of great importance for theories of the origin of cosmic-ray electrons. With the exception of the Crab Nebula, which is in a class by itself (cf. also Minkowski, Paper 62), all the remnants form a homogeneous class with spectral indices varying from − 0·77 to − 0·4. As noted by Baldwin (Paper 56, Section 6 and Table 2), all the old remnants seem to reach a limiting index of about − 0·4. Furthermore all of them have straight-line spectra down to at least 10 cm wavelength, and some even till 3 cm. It has been suggested that the limiting value of − 0·4 is due to the fact that the electrons in the old remnants are really the background cosmic-ray electrons, and the curvature of the background spectrum is pushed up to higher frequencies by the stronger magnetic fields in these remnants. This mechanism would seem to require fields 100 times stronger than the background fields, at the same time leaving open the question of the origin of the electrons.

I suggest that all the supernova remnants (except of course the Crab) start their life with a spectral index of about − 0·8, and during their evolution lose part of the original electrons to the outside, as seems to be the case in the Cas A remnant. The remaining electrons are slowly redistributed among the tangled magnetic fields of the shell, such that a correlation is established between regions of strong magnetic fields and higher-energy electrons. In this case the spectrum will become flatter, depending on the degree of correlation. The limiting spectral index of − 0·4 may then be due to a dynamic balance in the magnetic regions of the shell. On the basis of this scheme it is possible to work out a consistent theory of the origin of cosmic-ray electrons and of the evolution of supernova remnants.

S. A. Colgate asks Baldwin: Are there any polarization measurements of the Tycho Nebula, and any measurements at 21 cm?

Baldwin answers: We do not yet know. There is probably little polarization at 408 MHz. There may well be at 1407 MHz, but only further observations will show. We have not made measurements of the 1420-MHz line in Tycho's Supernova.

Oort asks: Is the distance to this source not too large, and its latitude too small, to expect that any initial polarization would have been preserved?

Baldwin answers: If there is a polarized source in Tycho's Supernova, then I think the differential interstellar Faraday rotation for different points in the 23″ (arc) beam would not be sufficient to make the polarization unobservable.

REFERENCE

Seeger, C. L., Westerhout, G., Conway, R. G., Hoekema, T. 1965, *Bull. astr. Inst. Netherl.*, **18**, 11.

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Chapter III B

The Galactic Magnetic Field

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'We reached the happy situation where residuals were of the same order as the effect we were seeking, namely, somewhere below the noise.'

G. L. Verschuur, in Paper 66

64. OBSERVING THE GALACTIC MAGNETIC FIELD

(Introductory Report)*

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ABSTRACT

Various methods of observing the galactic magnetic field are reviewed, and their results summarized. There is fair agreement about the direction of the magnetic field in the solar neighbourhood: $l = 50°$ to $80°$; the strength of the field in the disk is of the order of 10^{-5} gauss.

1. INTRODUCTION

Measuring the polarization and thus mapping the magnetic field has been a prime desideratum in galactic radio astronomy, since in 1955 optical polarization measurements proved the operation of the synchrotron emission mechanism in the Crab Nebula. The theoretical problems, which led to a heavy battle between the champions of strong fields (20 micro-gauss) and those of weak fields (2 μG) at the 1961 Princeton Symposium (Woltjer 1962), at present seem to have been somewhat eased but not solved. On the other hand, the amount and quality of available observational data are surprising. Some of these are very recent and should await a more thorough discussion by the authors themselves.

*The following text is only a brief and incomplete summary of the paper given at the Noordwijk Symposium. The full text has been published elsewhere (Van de Hulst 1967).

2. METHODS FOR OBSERVING THE GALACTIC MAGNETIC FIELD

Table 1 presents a list of observed effects from which we may infer something about the strength of the magnetic field, or about its direction or topology, or about both. The markings are conservative and subjective. The following discussion is restricted to brief remarks about a few of these methods.

a. Optical interstellar polarization

Measurements of direction and degree of polarization are now available for thousands of stars. The alignment of electric vectors (and thus of the magnetic field projected on the sky) parallel to the galactic equator is most perfect near $l = 140°$ and completely lacking near $l = 80°$; these probably are the respective directions where we look across and along the local spiral arm. Correlation studies of polarization in clusters indicate a microscale in the magnetic field of the order of 1 pc. Our knowledge of shape and composition of the grains is still too poor to allow reliable determination of the field strength from the measured polarization.

Table 1

Observational data about the galactic magnetic field

	Magnitude	Direction, topology
Optical interstellar polarization	q	f
Shapes of filamentary nebulae	—	q
Cosmic-ray energy density and confinement	q	q
Cosmic-ray anisotropy	—	q
Cosmic-ray electrons plus non-thermal radio emission	f	—
Zeeman effect, H	q	—
Zeeman effect, OH	—	—
Polarization of non-thermal radio emission	—	f
Faraday effect	f	f

Key: — no data or don't believe
q questionable or marginal
f fair or fine

b. Cosmic-ray energy density

From an application of the virial theorem to the galactic halo one may, setting the total magnetic energy equal to the integrated pressure, derive the magnetic field strength: $B = 7\ \mu G$. This is at most a vague estimate.

c. Spectra of cosmic-ray electrons and of non-thermal radio emission

The principle of this determination is straightforward. Synchrotron emission comes from fast electrons in a magnetic field. If we can measure the emission by observing the non-thermal radio continuum, and the electrons by detecting them as cosmic-ray electrons near the Earth, then we can calculate the field strength. But the practical execution involves a number of uncertainties.

(*i*) To convert the observed radio brightness into volume emissivity, we must decide upon the size and structure of the emitting region. Baldwin (Paper 56) has reviewed the problems of halo and disk, spurs and supernova remnants.

(*ii*) Reliable measurement of the cosmic-ray electrons among the many other particles now appears possible. Figure 1 in Paper 74 shows the energy spectrum of cosmic-ray electrons compiled by Y. Tanaka.

(*iii*) Is the electron density measured near the Earth typical for that in interstellar space? The change in slope in the energy spectrum near 1 GeV is probably due to solar modulation, which would leave the electrons of higher energy unaffected. A more secure answer may have to await observations spanning a full solar cycle.

Independent estimates of the disk field (see also Davies, Paper 57) range from 9 to 20 μG. The slope $\gamma = 2{\cdot}3$ of the observed electron spectrum in the range 2 to 30 GeV would give a radio spectral index $\alpha = \frac{1}{2}(\gamma - 1) = 0{\cdot}7$, well within the range of values determined by direct observation.

(*d*) *Zeeman effect*

For a discussion of the Zeeman effect in the 21-cm line, see Verschuur (Paper 66). In interpreting the small field strengths found, one should keep in mind that the field in the dense absorbing clouds may actually be weaker than generally in the disk.

Robinson (Paper 7) has discussed the polarization phenomena observed in the OH lines. As long as the excitation conditions of these lines remain enigmatic, it is hard to take quantitative results for the field strength seriously. The qualitative argument that circular polarization can be produced only in the presence of a magnetic field stands unchallenged.

(*e*) *Polarization of non-thermal radio emission*; *Faraday effect*

The polarization of synchrotron emission shows the existence of a magnetic field at the source of radiation; the Faraday effect demonstrates a field along the line of sight. The discussion of these two topics cannot be quite separated.

(*i*) *Continuum polarization surveys*

About a dozen surveys are now available (Van de Hulst 1967, Table 2). The maps usually display polarized intensity and position angle at each observed point. Since these quantities form coherent patterns over 10° or more on the sky, the magnetic fields do not appear to be tangled on a small scale; 40 pc may be a representative value of the coherence scale.

Comparison of the spectra of the total brightness and of the polarized component (Van de Hulst 1967, Figure 2) brings out, as their most striking feature, the existence of a strong depolarization. The theoretical synchrotron radiation of electrons with isotropic velocities in a homogeneous magnetic field has the degree of polarization

$$p = (\gamma + 1)/(\gamma + 7/3), \qquad (1)$$

where γ is the exponent of the electron energy spectrum. The value $\gamma = 2{\cdot}4$ gives $p = 0{\cdot}72$. Observed degrees of polarization range from 50 to 3% and lower.

Since no physical effect will destroy the polarization, the explanation must be sought in some superposition. Many possibilities are open: superposition of thermal emission,

which is unpolarized; superposition of different intrinsic directions of polarization within the beam; different intrinsic directions of polarization along the line of sight. Further, the Faraday effect may rotate by different amounts the radiation emitted at different distances along the line of sight, or at different directions within the beam, or even at different frequencies within the band. The rapid increase of polarization with frequency points very clearly to Faraday effect. The currently popular explanation is that only the relatively nearby regions contribute to the observed polarization. The emission at greater distances arrives with so many different angles of rotation that by superposition it is virtually unpolarized. Faraday rotation turns the plane of polarization by $R\lambda^2$ radians where the rotation measure, R, is given by

$$R = 0{\cdot}81 \int n_e(B \cos \theta)\mathrm{d}s, \tag{2}$$

with λ = wavelength in meters, n_e = electron density in cm^{-3}, $B \cos \theta$ = longitudinal component of field strength in micro-gauss, $\mathrm{d}s$ = element of line of sight in parsec.

(*ii*) *Mathewson's belt*

Maps of the polarization at various frequencies suggest that the Faraday rotation becomes zero near $l = 140°$ at low galactic latitudes, with the magnetic field parallel to the galactic equator and perpendicular to the line of sight; we call this region the ***fan region***. Maps of the entire sky reveal the existence of a large-scale feature familiarly called *Mathewson's belt*. With hardly any exception all places where the observed polarization is relatively strong fall in a belt, about 60° wide, cutting the galactic equator at $l = 320°$ to 20° and at $l = 120°$ to 180°, and perpendicular to it. This belt would be the locus of directions perpendicular to the local magnetic field, where Faraday rotation is smallest and synchrotron polarization strongest.

(*iii*) *Rotation measures from extragalactic sources*

Whereas the galactic polarization studies give rotation measures of 0 to 5, the values derived from observations of extragalactic radio sources are typically 10 to 100, or even larger. Three possible causes of this difference are: Faraday rotation in the extragalactic source; Faraday rotation in the more distant parts of the Galaxy, which are virtually depolarized in the continuum studies; the fact that determinations from the observed continuum polarization constitute a selection of regions where the rotation measure is small. Different authors assess these explanations with different weights. Probably further model calculations and statistical studies will be necessary before a conclusion can be reached.

The work of Gardner and Davies is discussed separately by Davies (Paper 67). Mathewson and Milne note that large rotation measures occur systematically outside Mathewson's belt, which is understandable if this belt is more than a local phenomenon. The absence of high degrees of polarization at low latitudes in the general region of the galactic centre (Bologna, McClain and Sloanaker) suggests a fine structure of the order of 1 pc in the magnetic field.

3. CONCLUSIONS

A fair measure of agreement exists about the direction of the magnetic field in the solar neighbourhood. Table 2a summarizes directions where we look along the field (and directions 90° away from those where we look perpendicularly to the field). For comparison, Table 2b gives the direction of the local spiral arm (Sharpless 1965). The values

quoted are all uncertain by at least 10°, even in definition. Much depends on the definition of 'local' in this context. The comparison does relieve us somewhat from the worry that the astronomical studies of magnetic fields might not be relevant at all on the small scale covered by cosmic-ray studies.

Table 2a

Direction of the magnetic field in the solar neighbourhood

Method of determination	Galactic longitude
Optical polarization	50°—80°
Cosmic-ray anisotropy	62°
Polarization 'fan'	50°
Mathewson's belt	70°
Rotation measures of extragalactic sources	70°—110°

Table 2b

Direction of the local spiral arm (Sharpless 1965)

Tracers	Galactic longitude
O-associations	50°
H II regions	60°
H I gas (21 cm)	70°

The question of topology, whether the directions just quoted are the direction of a wiggly but continuous tube of force, or just the predominant direction of a more tangled field, remains open. The microscales of the order of 1 pc suggested by some optical and radio studies should warn us not to take the simplest picture for granted.

The question of magnitude remains very much in the air. The statement 'of the order of 10 micro-gauss' seems all right. But factors of the order of 3 in the field, i.e. 10 in the pressure, which would make an enormous difference to the dynamical picture, cannot yet be firmly decided by direct observation.

REFERENCES

Sharpless, S. 1965, in *Galactic Structure*, Eds. A. Blaauw and M. Schmidt, Vol. V in the series: *Stars and Stellar Systems*, Univ. of Chicago Press, Chicago, p. 131.
Van de Hulst, H. C. 1967, *A. Rev. Astr. Astrophys.*, **5**, in press.
Woltjer, L. (Ed.) 1962, *Interstellar Matter in Galaxies*, W. A. Benjamin, Inc., New York.

Discussion

J. R. Shakeshaft: Van de Hulst commented (Section 2(*e*) *iii*) upon an apparent discrepancy between the rotation measures obtained for galactic radiation and for discrete sources; the latter values are often larger by an order of magnitude. This is surely due to the fact that the rotation measures for the galactic polarized radiation are determined in directions nearly *perpendicular* to the field, where the polarization tends to be large, whereas many sources are observed *along* the field direction. The longitudinal component of field is therefore much less in the former case than in the latter.

J. Tinbergen: In the interpretation of multi-wavelength polarization observations there occurs an equation of this general form:

$$\frac{W(\lambda^2)}{A(\lambda^2)} = \int_{-\infty}^{+\infty} w(\xi) \exp(2\mathrm{i}\ \lambda^2\ \xi)\ \mathrm{d}\xi, \tag{3}$$

where $W = Q + \mathrm{i}U = T_{\mathrm{p}} \exp(2\mathrm{i}\ \theta)$ is the observed polarization, A is the intrinsic wavelength dependence of the polarized radiation,

$$\text{and } \xi = \int_{\text{source}}^{\text{observer}} n_{\mathrm{e}} \cdot B_{||} \cdot \mathrm{d}s; \tag{4}$$

Q and U are Stokes parameters, T_{p} is the polarized intensity, θ the position angle of polarization, n_{e} the electron density, and $B_{||}$ the longitudinal component of the magnetic field strength.

In the, to my knowledge, only published paper on this subject, B. J. Burn (1966, *Mon. Not. R. astr. Soc.*, **133**, 67) uses the term *Faraday depth* for the quantity ξ. Several people have used *rotation measure*, but others prefer to keep this term for the observed quantity $\mathrm{d}\theta/\mathrm{d}\lambda^2$, in general a function of wavelength. Although in the simplest case ξ and $\mathrm{d}\theta/\mathrm{d}\lambda^2$ are identical, their meaning is different, the latter being an observable and the former a property of the propagation path in the physical universe.

I suggest that Commission 40 of the IAU agree on a recommended name for these quantities and that meanwhile authors adhere to Burn's convention:

$$\xi = \text{Faraday depth}$$
$$\mathrm{d}\theta/\mathrm{d}\lambda^2 = \text{rotation measure.}$$

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65. MAGNETIC-FIELD STRENGTHS FROM OPTICAL POLARIZATION DATA

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Van de Hulst (Paper 64, Table 1) has marked optical polarization as a questionable or marginal source of information concerning magnetic field strengths. Rather than arguing about this—I should rate this method as $q+-$, or quarrelling about the term 'model-sensitive results', I wish to stress the historical point that as recently as two years ago there were still some who questioned that optical polarization was definitely due to magnetically-oriented interstellar particles.

The following results are based on detailed calculations extending work by Jones and Spitzer (1967) on the magnetic orientation mechanism, and on calculations developing further the work by Greenberg and Shah (1966) on the scattering by cylindrical particles.

Let us define $(\Delta m_p/\Delta m)_0$ as the ratio of polarization to extinction (both in magnitudes) for perfect Davis-Greenstein orientation. By perfect Davis-Greenstein orientation I mean the case in which the field is perpendicular to the line of sight and the particles are spinning entirely in a plane defined by the magnetic field. For imperfect orientation the ratio of polarization to extinction is reduced by a factor R, defined by

$$\Delta m_p/\Delta m = (\Delta m_p/\Delta m)_0 \, R.$$

The reduction factor may be found analytically for small particles which satisfy the Rayleigh approximation criterion. Consider next spheroidal particles spinning about their short axes, and let the angle β between their spin axes and the magnetic field direction be distributed according to

$$f(\beta) = \frac{\xi}{2\pi}(\xi^2 \cos^2\beta + \sin^2\beta)^{-3/2}, \tag{1}$$

We may show that the reduction in polarization (and, consequently, in the ratio of polarization to extinction) is given by the function

$$R(\xi) = \frac{3}{2(1-\xi^2)} - \frac{1}{2} - \frac{3\xi}{2}\frac{\arcsin\{(1-\xi^2)^{1/2}\}}{(1-\xi^2)^{3/2}} \;. \tag{2}$$

In column 2 of Table 1 we list the ratios $(\Delta m_p/\Delta m)$ as calculated for spinning infinite dielectric cylinders, whose distribution of orientations is as given by equation (1). We see that these ratios decrease with increasing ξ, in a way closely following that of the reduction factor $R(\xi)$ calculated for Rayleigh-size particles. Therefore, it is convenient and valid to use the analytical form of $R(\xi)$ given in (1), even for particles whose sizes are comparable with the wavelength of the radiation. We further note that equation (1) defines the degree of magnetic orientation, if we assign to the parameter ξ the physical form

$$\xi = (1 + \tau_c/\tau_0)^{-1/2} \;,$$

Table 1

Polarization/extinction ratio, disorientation reduction factor, and related quantities

ξ	$(\Delta m_p/\Delta m)$	$R(\xi)$	τ_c/τ_0	B (10^{-5} gauss)
0·0	0·20	1		∞
0·1	0·15	0·77	99	10
0·3	0·09	0·49	10·1	3·3
0·5	0·05	0·29	3·0	1·7
0·7	0·025	0·15	1·04	1·02
0·9	0·007	0·05		

where τ_0 = orientation relaxation time;
τ_c = collisional relaxation time (for collisions of gas atoms with the grain).

It may be shown that

$$\frac{\tau_c}{\tau_0} = \left(\frac{2\pi}{m_H\, kT}\right)^{1/2} \frac{\chi''}{\omega} (2a\, n_H)^{-1} B^2, \tag{3}$$

where we define:

m_H = mass of hydrogen atom;
k = Boltzmann constant;
T = gas temperature;
χ'' = imaginary part of magnetic susceptibility;
ω = angular velocity of spinning grain;
a = particle radius (cylinder radius, or minor radius of prolate spheroid);
n_H = number density of hydrogen atoms;
B = magnetic field.

Using $\chi''/\omega = 2{\cdot}5 \times 10^{-12}\, T_g^{-1}$ (where T_g = grain temperature = 10 °K), T = 100 °K, n_H = 10 atoms/cm³, $a = 2 \times 10^{-5}$ cm, one finds: $\tau_c/\tau_0 = B^2$, where B is in units of 10^{-5} gauss.

We see from Table 1 that at $\Delta m_p/\Delta m = 0{\cdot}025$, which is the minimum ratio observed for low dispersion in planes of polarization, the required field—if viewed perpendicular to the line of sight—is $B = 1 \times 10^{-5}$ gauss.

A non-uniform magnetic field may be taken into account. Consider a magnetic field whose distribution in space is according to $F(B) \propto \exp\{-(B_x^2 + B_y^2)/a^2 - B_z^2/c^2\}$, where the z-axis is directed along a spiral arm. This distribution function, with $c > a$, implies that the average direction of the magnetic field is along the spiral arm, with deviations in angle χ from this direction distributed according to

$$f(\chi) = \frac{a}{2\pi c}\left(\frac{a^2}{c^2}\cos^2\chi + \sin^2\chi\right)^{-3/2}. \tag{4}$$

This randomness in the magnetic-field direction leads to a further reduction in the ratio of polarization to extinction, by the factor $R(X)$, where $X = a/c$. Using the tabulated values of R we see that a spheroidally distributed magnetic field with $c/a = 3$ produces a reduction $R(X) = 1/2$, relative to a uniform magnetic field of the same absolute strength. It should be noted that the degree and kind of polarization may, with the above model, be correlated with, for example, variation in the wavelength dependence of polarization. This work will appear in more detail in the *Astrophysical Journal.*

REFERENCES

Greenberg, J. M., Shah, G. 1966, *Astrophys. J.*, **145**, 63.
Jones, R. V., Spitzer, L., Jr. 1967, *Astrophys. J.*, **147**, 943.

I.A.U. Symposium no. 31, 1967

66. THE ZEEMAN EFFECT IN INTERSTELLAR CLOUDS

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ABSTRACT

The interpretation of Zeeman-effect measurements in terms of interstellar magnetic fields is strongly involved with the problems of the nature of interstellar clouds, and of their relationship to the structure of the field. The best measurements furnish, for the mean longitudinal component of the spectrum of Tau A, a value of $+ 1\cdot 1 \pm 3\cdot 0\ \mu$G (micro-gauss), and for that in the Orion-Arm feature in Cas A, $- 0\cdot 8 \pm 3\cdot 5\ \mu$G. These values are consistent with an upper limit of 7 μG to a uniform magnetic field, pervading the absorbing clouds and directed parallel to the local spiral arm.

1. INTRODUCTION: WHAT IS AN INTERSTELLAR CLOUD?

In view of the negative results presented in this paper, and bearing in mind in particular Van de Hulst's cautionary remarks (Paper 23) about interstellar clouds, we should perhaps re-title this communication: '*Non-existent Zeeman effects in non-existent interstellar clouds*'.

Let us first be quite sure about the regions of space with which we are dealing. The 'normal' distribution of neutral hydrogen in the galactic plane shows several types of irregularities:

(*a*) density variations;
(*b*) temperature variations;
(*c*) variations of the velocity distribution.

Various combinations of these irregularities are sometimes called 'interstellar clouds'. The combinations with which we are here concerned involve colder regions of possibly higher density than the remainder of the neutral hydrogen.

In the direction of the radio sources Taurus A and Cassiopeia A we see considerable amounts of cold gas whose velocities lie in a narrow range. This matter produces absorption of the continuum radio emission of these sources over a limited frequency range near 1420 MHz. The absorption profiles show distinct peaks and minima as well as considerable fine structure. The process of fitting Gaussian components to account for the structure in the spectrum has already been discussed (Paper 1). Such components are sometimes thought to be due to distinct 'clouds', each with a specific temperature and density. This is a dangerous step however. We must therefore bear in mind that the interpretation of the absorption or emission profiles in terms of a number of such 'clouds' is far from understood.

If we were to observe one small cloud of gas having a particular temperature and moving with a particular velocity, we should see in the spectrum a single Gaussian absorption feature, whose frequency width is determined by the excitation temperature. If this cloud were then permeated by a uniform magnetic field with a component along

the line of sight, the absorption line would be split into two circularly polarized line components in a known manner. The techniques and problems of measurement of this Zeeman effect have been adequately described elsewhere. The separation of the line components is, of course, determined by the magnetic field strength: it amounts to 2·8 Hz per micro-gauss. No such single, narrow spectral feature has yet been observed however. Only the deep feature in the Tau A absorption profile comes near to being a single Gaussian.

Before interpreting any results, we must therefore have a clearer picture of what the structure seen in the profiles really means in terms of the distribution of interstellar neutral hydrogen into 'clouds'.

Putting these doubts aside for a moment, let us look at the measurements.

2. THE MEASUREMENTS

At Jodrell Bank, seven separate experiments have been performed since 1960. These are referred to as Zeeman 0 to Zeeman VI. Part of the Zeeman IV observations were thought to be indicative of a very large magnetic field in one component of the Tau A absorption profile (Davies *et al.* 1962). This result has *not* been confirmed. The particular observations indicated an effect much greater than the observed noise, but in fact not significantly greater than the *expected* noise level. It is fair to say that, since then, we have come to a better understanding of this method of observation.

Residual effects have always been a problem in these measurements. The Zeeman VI data, however, produced the happy situation where the residuals were of the same order as the effect we were seeking, that is, somewhere below the noise.

Figures 1 and 2 summarize the results. Noise levels on the various runs are influenced by the receiver noise and by the contribution to the aerial temperature produced by the radio source. One of the best runs on Tau A (Figure 1 G) did not uniformly cover the complete frequency range desired and was therefore not included in the final analysis. It is, however, shown for comparison, in uncorrected form.

Table 1 compares our results with those published by others. The results refer to

Table 1

Results of Zeeman-splitting measurements in the absorption spectra of Cassiopeia A and Taurus A

Reference	Bandwidth of observations (kHz)	Longitudinal component* of magnetic field (μG)	
		Cas A (Orion Arm)	Tau A
Davies *et al.* (1963)	5	$-4·3 \pm 3·8$	$+6·4 \pm 4·5$
Verschuur (1965)	3	$-2·2 \pm 4·7$	$-1·5 \pm 3·0$
Morris *et al.* (1963)	6	$+2 \pm 4$	-9 ± 14
Weinreb (1962)**	7·5		
Data A		$+3·0 \pm 2·4$	$-1·5 \pm 2·0$
Data B		$-0·5 \pm 2·0$	———

* A positive field is directed away from the observer. The unit is 1 μG = 1 micro-gauss = 10^{-6} gauss.

** For this comparison I have treated Weinreb's data points in a similar way to the data in our analysis.

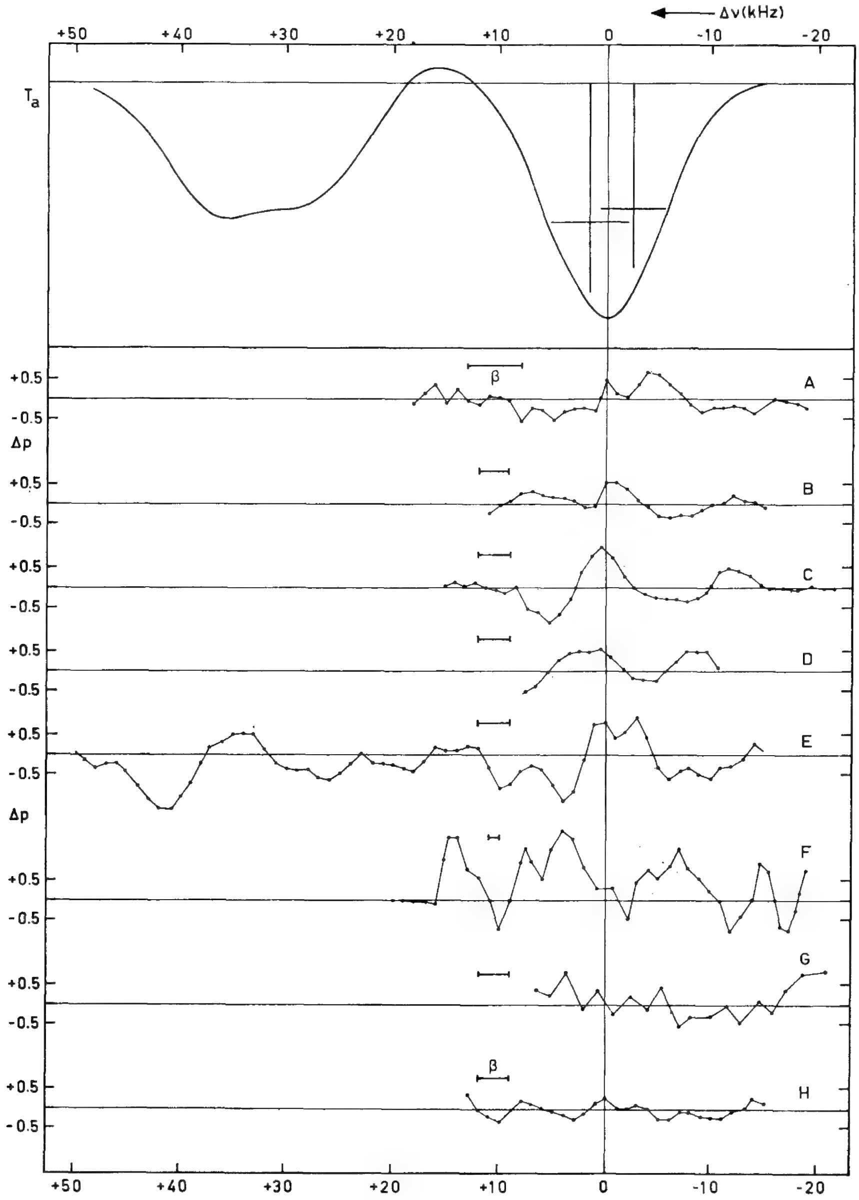

FIG. 1. Zeeman effect in absorption spectrum of Taurus A. Uppermost curve: absorption profile; ordinate: aerial temperature; abscissa: frequency shift with respect to the centre of gravity of the deepest absorption feature. Components indicated by crosses. Broken curves: Zeeman profiles; ordinate: left-hand minus right-hand polarization, in per cent of the line depth. Bandwidth indicated by β. The Zeeman profiles were obtained from observations identified as follows: A, Sum of Zeeman II (1961) and III (1962); B, Zeeman IV, scanning; C, Zeeman IV, integrators, published data; D, Zeeman IV, integrators, second group, limited coverage; E, Zeeman V, integrators; F, Zeeman VI, scanning; G, Zeeman VI, integrators, limited coverage; H, Sum of B, E and F.

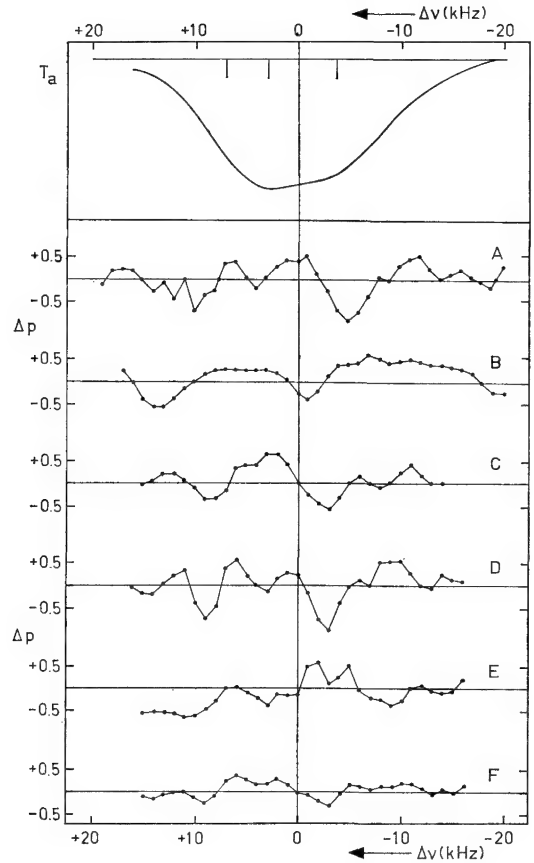

FIG. 2. Zeeman effect in absorption spectrum of Cassiopeia A (Orion-Arm component). Uppermost curve: absorption profile; ordinate: aerial temperature; abscissa: frequency shift with respect to centre of gravity of absorption feature. Suggested components indicated. Broken curves: Zeeman profiles; ordinate: left-hand minus right-hand polarization, in per cent of the line depth. Observations identified as follows: A, Zeeman III; B, Zeeman IV, scanning; C, Zeeman IV, integrators; D, Zeeman V, integrators; E, Zeeman VI, integrators; F, total of above B, C, D and E.

a 'general field', that is a uniform field penetrating equally all the matter producing the absorption feature. In the case of the Orion-Arm feature in Cas A we already know (Barrett *et al.* 1964, see also Paper II) that the OH absorption spectra indicate at least two separate 'clouds'. Therefore we should bear in mind that different fields might well exist in different 'clouds', and might produce a more complicated Zeeman picture.

Combination with equal weight of the three results with lowest errors on Tau A gives a mean value of $+1 \cdot 1 \pm 3 \cdot 0\,\mu$G for the general field. The four values for Cas A give a mean result of $-0 \cdot 8 \pm 3 \cdot 5\,\mu$G. The errors quoted are twice the standard deviation.

3. INTERPRETATION

These observations give only the mean longitudinal component of the magnetic flux in the so-called 'clouds'. We do not know anything, however, about the distribution of this field. The following questions require consideration before we can embark on any interpretations:

(*a*) Are the features in the absorption profiles indicative of well-defined, specific regions ('clouds') in space?

(*b*) Do magnetic fields penetrate the 'clouds'? If the model suggested by Clark (1965) – small, cool, dense concentrations in a hot, less dense medium – is valid, then the cool clouds might well be diamagnetic, as has been suggested by Woltjer. The problem needs further investigation.

(*c*) If the fields do penetrate the clouds, are the fields at different parts of the line of sight sufficiently ordered to enable a net Zeeman effect to be observed; and how should we account for the degree of disorder?

(*d*) Is it possible that field lines form closed loops within these cool condensations? In that case we should see no resultant Zeeman effect at all, no matter how strong the field, unless of course we were inside such a 'cloud'.

Optical and radio data on polarization position angles, particularly those from high-resolution radio observations, will provide important information about fine structure in the interstellar magnetic field. This has a direct bearing on question (*c*) above.

At this stage one can only assume a uniform magnetic field, pervading the 'clouds' which produce the absorption features, and directed parallel to the local spiral arm (perpendicular to $l^{II} = 140°$). Then, from the results presented here one finds, by suitable geometry, a mean upper limit for this field of about 7×10^{-6} gauss. I must stress again, however, that this approach involves many assumptions.

What of the future of such measurements? Perhaps the many surveys of galactic neutral hydrogen could produce a very narrow (say 10 kHz wide), strong emission or absorption feature, isolated in space from any other neutral hydrogen. This 'real cloud' would then be ideal for a search for a magnetic field. If this cloud also contained dust, polarization measurements might prove the existence of a magnetic field in the cloud, and Zeeman measurements would then yield a quantitative value for the field strength.

In the meantime, let us not take the interpretation of these values too far; they are after all only negative results for a few, probably non-typical, cold absorption features of large optical depth. We need to know a lot more about the interstellar medium and its magnetic-field structure before we can use such numbers to fit our theories.

REFERENCES

Barrett, A. H., Meeks, M. L., Weinreb, S. 1964, *Nature*, **202**, 475.
Clark, B. G. 1965, *Astrophys. J.*, **142**, 1398.
Davies, R. D., Shuter, W. L. H., Slater, C. H., Wild, P. A. T. 1963, *Mon. Not. R. astr. Soc.*, **126**, 353.
Davies, R. D., Verschuur, G. L., Wild, P. A. T. 1962, *Nature*, **196**, 563.
Morris, D., Clark, B. G., Wilson, R. W. 1963, *Astrophys. J.*, **138**, 889.
Verschuur, G. L. 1965, Ph.D. thesis, University of Manchester.
Weinreb, S. 1962, *Astrophys. J.*, **136**, 1149.

I.A.U. Symposium no. 31, 1967

67. GALACTIC MAGNETIC-FIELD MODELS DERIVED FROM FARADAY-ROTATION DATA

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ABSTRACT

The distribution of rotation measures for 86 sources suggests a two-component model for the magnetic field: a disk component directed toward $l = 95°$, and a component in the local spiral arm, directed along $l = 70°$ and $250°$, with opposite senses above and below the plane. The latter may be due to a looped field in a cloud surrounding the Sun; its net flux is 3·5 micro-gauss.

The Faraday-rotation data for 86 sources given by Gardner and Davies (1966) allow the deduction of some basic properties of the structure of the galactic magnetic field. The systematic variation of the rotation measure (cf. Van de Hulst, Paper 64, Section 2(*e*)*i*),

$$R = 8{\cdot}1 \times 10^5 \int n_e B_{||} ds,$$

with galactic coordinates shows the galactic origin of the Faraday rotation; here R is in rad/m^2, n_e is the electron density in cm^{-3}, $B_{||}$ is the magnetic-field component along the line of sight in gauss, and ds is the line element in pc.

Two main features of the distribution of R can be identified. One component has a high rotation measure ($R > 50$) and is confined to a region within about 10° of the galactic equator; it results from a magnetic field directed in the sense of galactic rotation, toward $l^{II} = 95° \pm 10°$. The latitude width of this component agrees with that expected for a field embedded in the ionized-hydrogen layer of the galactic disk. The other component has smaller values of R and is found at higher latitudes. The magnetic field in this component has opposite senses above and below the plane, and is directed approximately along the line $l^{II} = 70°, 250°$.

The second component of the distribution of R has a much larger latitude width, suggesting an axial ratio nearer to unity for the distributions of electron density and magnetic field. I suggest that this component arises nearby, in a magnetic field in the local spiral arm. One reason for this conclusion is that a field in the same direction is already known to exist in this region from studies of the polarization of starlight. Another reason is that the areas of strong polarization in the galactic background (Mathewson and Milne 1964) follows closely the line of zero rotation measure in the map of the R distribution; it is known that the regions of background polarization are close by (Van de Hulst, Paper 64, Section 2(*e*)*i*). The data at present available can be fitted with a Gaussian distribution of n_e and B in a cloud in which the Sun is situated. The field in this model is in the form of loops or tightly wound helices, lying in a plane approximately perpendicular to the galactic plane and parallel to the direction $l^{II} = 70°, 250°$. The observed distribution of R would fit a looped field lying within the Local System (or Gould Belt, see Eggen 1961), for example.

An estimate of the magnetic-field strength within the Galaxy is possible if the electron density can be calculated. The only way to obtain the electron density in the regions of interest is from a determination of the emission measure $E \equiv \int n_e^2 \, ds$. Since the distribution of electron density is known to be irregular, the r.m.s. density obtained is an overestimate of the mean electron density. One may derive the value of α, the fraction of space where the gas is ionized, from a number of different observations such as the statistics of neutral-hydrogen clouds, optical data on interstellar clouds, radio measurements of H II regions in the galactic disk, and analyses of the H II regions in complexes such as Cygnus X. The value of α found is 0·05, within a factor of 3, so that the derived magnetic-field strength is uncertain by a factor of $\sqrt{3}$. From the analysis by Ellis and Hamilton (1964) of the absorption of low-frequency galactic background radiation in the latitude range 30° to 60°, I obtain, for the electron density in the nearby spiral arms, $\langle n_e^2 \rangle^{1/2} = 0{\cdot}027 \text{ cm}^{-3}$, within a factor of 1·7. The corresponding value of the net magnetic flux is 4·7 micro-gauss (μG) in the nearby arms. A similar calculation, based on the low-frequency absorption and the rotation measure for the source Cygnus A, gives a flux of 4·3 μG. The flux in the local cloud discussed above, obtained from rotation measure, dimensions and electron density of the Local System, is 3·5 μG. These values are lower by a factor of three than the field strengths apparently required for the observed synchrotron emission from the disk of the Galaxy (cf. Paper 57). This difference would be explained by a tangled or looped component of the galactic field, which would contribute to the total field strength, but not to the net flux derived from Faraday-rotation or Zeeman-splitting measurements.

REFERENCES

Eggen, O. J. 1961, *R. Obs. Bull.*, no. 41.
Ellis, G. R. A., Hamilton, P. A. 1964, *Nature*, **204**, 272.
Gardner, F. F., Davies, R. D. 1966, *Austr. J. Phys.*, **19**, 129.
Mathewson, D. S., Milne, D. K. 1964, *Nature*, **203**, 1273.

Discussion

G. L. Verschuur: If Davies has used only published data, there are still too many ambiguous values of rotation measure to make this apparent field reversal above and below the plane a definite, established effect. This is particularly important above the plane in the region $l^{\text{II}} = 210°$ to 330°.

R. D. Davies answers: My data did not include any ambiguous values.

H. C. van de Hulst asks: Could Davies say something about Seymour's work?

Davies answers: P. A. H. Seymour (1966, *Mon. Not. R. astr. Soc.*, **134**, 389) has independently made a harmonic analysis of our Faraday-rotation data. He also found that the magnetic-field flux increases rapidly beyond the solar distance from the centre. His analysis did not take into account a local magnetic field as I have proposed.

Van de Hulst comments: I feel that we are still at a stage in which it is advisable to study plots of the rotation measures of all the individual sources, rather than contour diagrams (as used by Davies and Gardner), or coefficients of harmonic analysis (as derived by Seymour).

Chapter III C

The Galactic Nucleus

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'In short, there is non-conservation of everything.'
K. H. Prendergast, in Paper 51

68. SAGITTARIUS A

(Introductory Report)

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ABSTRACT

The available high-resolution observations of the complex of radio sources in the region of the galactic centre are reviewed and analysed. As noted by Downes and Maxwell, the spectrum of the strong central source, Sagittarius A, is markedly non-thermal (index 0·7) at high frequencies; below 3000 MHz the spectrum may be flat, but flux values obtained at high angular resolution are badly needed.

Various arguments indicate that the whole source complex is located near the nucleus of the Galaxy. From the short-wave observations collected by Downes and Maxwell dimensions, densities and masses are estimated for the thermal sources. The total mass of ionized hydrogen in these sources is about $10^6 M_\odot$; the mechanism of ionization is uncertain.

The non-thermal source Sgr A may be similar to the optical nuclei of external galaxies. Its synchrotron emission, as well as the outward motions and tilted features observed in the 21-cm line and continuum, are signs of activity in the galactic nucleus; but the time-scales of the various phenomena appear to disagree.

1. INTRODUCTION

A discrete radio source in the direction of the galactic centre was discovered by Piddington and Minnett (1951); they called it Sagittarius A (abbreviated Sgr A). Haddock, Mayer and Sloanaker (1954) showed, by observations at 9·4 cm, that it contains a component not resolved by their 25′ (arc) beam, superimposed on an extended component. Drake (1959), Parijskij (1959), and Biraud *et al.* (1960) independently demonstrated that the narrow component has an angular diameter of the order of 3′.5, and Drake has given the first high-resolution isophote map of the region, which has turned out to be quite complex.

In the last few years, numerous high-resolution observations have been carried out at centimetre wavelengths, and also at 408 MHz (74 cm) (Little 1966). At metre and

decametre wavelengths, the only measurements available are those with relatively poor resolution by Mills (1956, 1964) and Shain (1957). In addition, extensive observations have been made in the 21-cm line and the OH-lines; since these are discussed in detail by Kerr in Paper 42, we shall mention them only in passing. X-ray observations carried out above the atmosphere have revealed several sources in the region of the galactic centre, but none of these coincides with Sgr A (Clark *et al.*, 1965; see also Rossi in Paper 75).

Several review papers have discussed these observations, the most recent ones being those of Cooper and Price (1964), Parijskij (1964), Burke (1965), and Downes and Maxwell (1966); from the last one we have borrowed essential parts of the present report.

Since the position of Sgr A agrees quite accurately with that of the centre of symmetry of the Galaxy, there is general agreement that the source is situated at the galactic centre itself. It has indeed been used to define the origin of longitudes in the new system of galactic coordinates (Blaauw *et al.*, 1960).

We shall restrict ourselves here to a study of the continuous radio emission of the galactic centre, making only occasional reference to measurements of the radio spectral lines and to optical observations; we shall also compare the structure of the galactic nucleus to that observed in the Andromeda Nebula, M 31.

2. THE RADIATION OF THE GALACTIC CENTRE AT CENTIMETRE WAVELENGTHS

The isophote maps obtained at different frequencies (a list is given in Table 1) are closely similar, provided their resolution is sufficient (better than 10′). The most detailed maps (Figures 1 and 2) show about eight small sources, approximately aligned on the galactic equator and superimposed on an extended component, which is centred on the strongest of the small sources.

Table 1

Principal isophote maps of the galactic-centre region

Frequency (MHz)	Resolution (minutes of arc)	Reference
15 500	2	Drake (1966)
15 500	2·2	Downes, Maxwell and Meeks (1965)
14 500	5·9	Hollinger (1965)
14 500*	3·4	Baars, Mezger and Wendker (1965)
8 250	4·2	Downes, Maxwell and Meeks (1965)
		Downes and Maxwell (1966)
8 000	6	Drake (1959)
5 000	4·1	Broten *et al.* (1965)
5 000	10·8	Maxwell and Downes (1964)
3 000	6·7	Cooper and Price (1964)
1 670	12·5	Robinson *et al.* (1964)
1 410	13·5	Kerr and Sinclair (1967)
1 390	35	Westerhout (1958)
85·5	50	Mills (1956)
19·7	84	Shain (1957)
		Shain, Komesaroff, Higgins (1961)

*The direction of increasing right ascension is in error.

a. The strong central source, Sgr A

For this strongest source we shall, following Downes and Maxwell (1966), reserve the name Sagittarius A. It has the following *position:* α (1950·0) = $17^{h}\,42^{m}\,28^{s} \pm 2^{s}$; δ (1950·0) = $-28°\,58'.5 \pm 0'.5$. Its galactic coordinates are therefore: $l^{II} = -2'.5$; $b^{II} = -2'.0$.

Its *dimensions* have been determined by a number of authors: Parijskij (1959, 1964), Lequeux (1962), Maltby and Moffet (1962), Downes *et al.* (1965), and others. They agree in finding a width at half-peak intensity of $3'.5 \pm 0'.5$; the source probably is slightly elongated along the galactic plane. No fine structure has been observed, but the angular resolutions employed have not been better than 1′ (Parijskij) or 2′ (Lequeux; Maltby and Moffet).

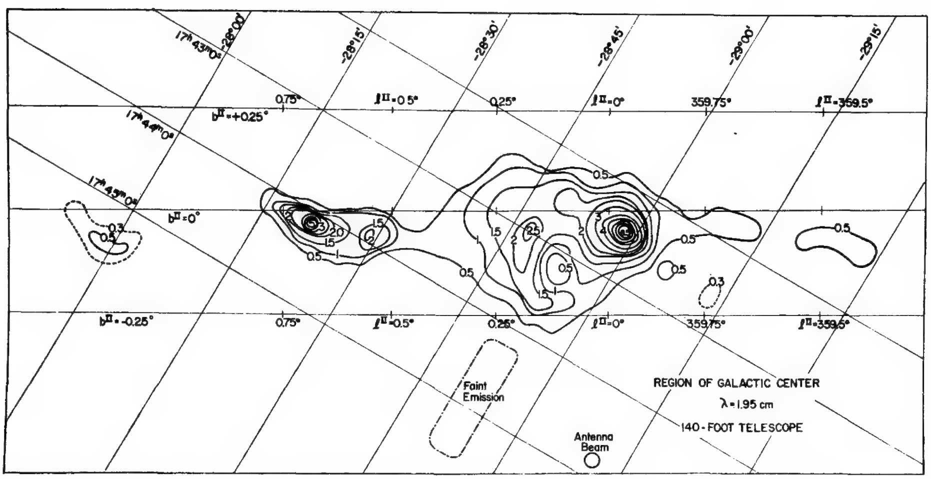

FIG. 1. Isophote map of the region of Sagittarius A at 1·95 cm wavelength. This map has been obtained by F. D. Drake with the 140-foot (43-m) telescope of the National Radio Astronomy Observatory at Green Bank, West Virginia, U.S.A. The contour values probably indicate brightness temperature within 30%. Note the shell structure centred at $l = +0°.1$, $b = -0°.15$. Right ascension and declination are shown for the equinox 1950·0.

Numerous measurements of the flux of Sgr A are available. From these, Downes and Maxwell (1966) infer that its *spectrum* is typically non-thermal between 3 and 15·5 GHz (10 and 1·9 cm): it is of the form $S(\nu) \sim \nu^{-\alpha}$, with $\alpha = 0{\cdot}70 \pm 0{\cdot}05$ according to the calibration by Kellermann (1964). Tolbert and Straiton (1965) have observed the galactic centre at 35 GHz (0·85 cm), but it is difficult to derive from their observations the flux of the component Sgr A at that frequency. We note that until 1965 it was thought that this source had a thermal spectrum.

No linear or circular *polarization* exceeding 2% has been detected in the source. This is not at all surprising, since the depolarization by Faraday rotation in the Galaxy must, undoubtedly, be considerable.

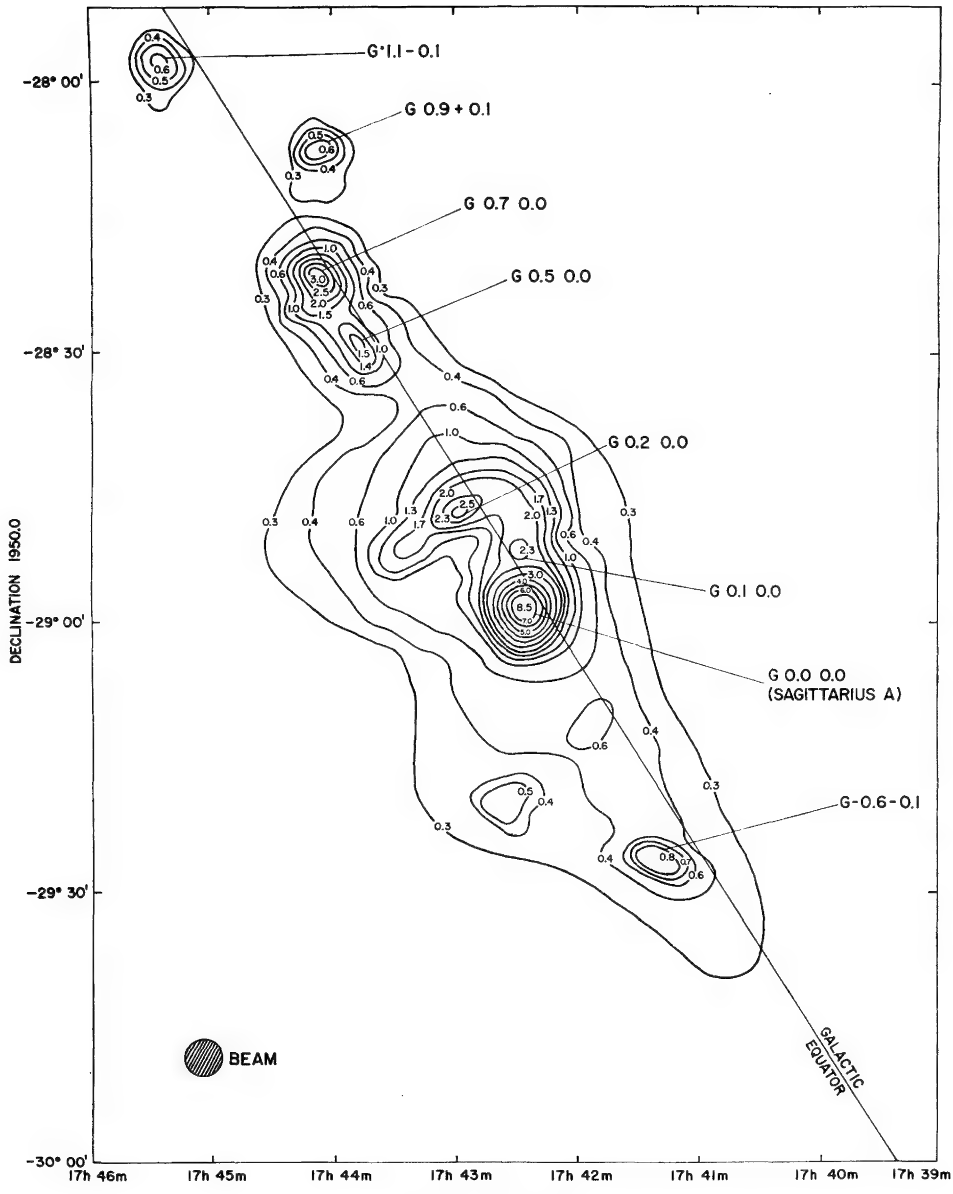

FIG. 2. Isophote map of the region of Sagittarius A at 3·6 cm wavelength. This map has been obtained by D. Downes and A. Maxwell with the 120-foot (37-m) Haystack radio-telescope of the Lincoln Laboratory, Massachusetts Institute of Technology, Cambridge, Massachusetts, U.S.A. Contour values represent antenna temperature. The nomenclature indicated for the sources, which is based on their galactic coordinates, is used throughout this paper.

b. The other small sources

Following Downes and Maxwell (1966), we shall denote the other sources in the neighbourhood of Sgr A by the letter G, followed by two numbers expressing, respectively, their galactic longitude and latitude in degrees and tenths. These other sources have angular dimensions of the order of $5'$ to $10'$ (see Table 3). Downes and Maxwell have studied their spectra; these are less well-determined than that of Sgr A, but in all cases the spectral index α is of the order of 0·1, characteristic of the thermal emission by an optically thin ionized gas. The observations by Little (1966) at 408 MHz indicate that several of the sources must have an optical thickness of the order of unity at this frequency, and that the source G 1·1 − 0·1 could be partially non-thermal; however, for these longer-wave observations the separation of sources and background is somewhat arbitrary.

Radio emission lines have been observed at the positions of two of these sources. The source G 0·7 0·0 shows the OH-line at 1667 MHz in emission (McGee *et al.*, 1965; Barrett and Rogers 1966). Mezger and Höglund (1967) have observed the 109α line of hydrogen in G 0·7 0·0 and G 0·2 0·0; this confirms that these sources* are H II regions.

c. The extended source

The discrete sources are superimposed on an extended component, whose dimensions at half-peak intensity are about $1^\circ\!.0$ in galactic longitude and $0^\circ\!.4$ in latitude, and which is equally visible by interferometry as on isophote maps. Downes and Maxwell (1966) have collected the measures of brightness temperature at the centre of this extended component. These measurements may be uncertain by more than 30%, owing to the difficulties connected with the subtraction of the galactic background. One finds: 0·6 °K at 14·5 GHz, 2·0 °K at 8 GHz, 4·6 °K at 5 GHz, 15·5 °K at 3 GHz and 60 °K at 1·4 GHz. Thus, the brightness temperature varies practically as the power − 2·0 of the frequency, which is characteristic of an optically thin thermal source.

3. OBSERVATIONS AT DECIMETRE AND METRE WAVELENGTHS

At frequencies smaller than 3000 MHz ($\lambda > 10$ cm), no observations have been made with pencil-beams sufficiently small to isolate Sgr A from the neighbouring sources, and the interpretation of interferometric observations is difficult because of the complexity of the region. Table 2 summarizes the attempts to determine the *flux of Sgr A*. The values obtained show considerable spread, but there is no systematic tendency for a stronger or weaker flux according to the type of instrument used or its resolution.

The spectrum of Sgr A is, therefore, unknown, but it is certain that its spectral index is smaller below 1400 MHz than at centimetre waves. This *curved spectrum* must be due either to a curvature in the energy spectrum of the relativistic electrons responsible for the radiation of Sgr A, or to absorption phenomena. In the latter case, one can immediately

*Mezger and Höglund (1967) denote these sources G 0.2−0.1 and G 0.7−0.1, on the basis of position measurements by Mezger and Henderson (1967). According to Mezger, the discrepancy between these designations and those of Downes and Maxwell (1966) used here may be either due to pointing errors of the telescopes or to the difference in angular resolution of the observations. —*Editor*.

exclude synchrotron self-absorption and Razin-Tsytovich absorption, unless one assumes a quite artificial, complicated model for the source.

The observations by Little (1966) at 408 MHz, with a resolution of $1'.5$ in α and 4° in δ, carry information of great interest. The right ascension measured for Sgr A is: $\alpha(1950) = 17^h 42^m 34^s.9$, i.e. $7^s \pm 2^s$ larger than the right ascension at centimetre wavelengths. This suggests that its western part is absorbed by an H II region in the foreground or within the source; but this H II region cannot be the extended thermal component, whose optical thickness at 408 MHz is only 0·1. The flux measured at 408 MHz is 385×10^{-26} W m^{-2} Hz^{-1}; this is three times smaller than would be expected from an extrapolation of the high-frequency spectrum derived by Downes and Maxwell (1966). An *absorption* by a factor 3 corresponds to an average optical thickness of about 1, which would be produced by an ionized gas at a temperature of 10^4 °K and an emission measure of 5×10^5 cm^{-6} pc. This emission measure is quite comparable to that of the small thermal sources in the vicinity; thus the absorption could simply be due to an extension of G 0·2 0·0 or G 0·1 0·0 in front of Sgr A. Nevertheless, Mezger and Höglund (1967) have not been able to detect the 109 α line of hydrogen in front of Sgr A, and this puts an upper limit of about 3×10^5 cm^{-6} pc on the emission measure. The detection by Dravskih *et al.* (1966) of the line 104α corresponds to an emission measure of about 10^5 cm^{-6} pc. The absorption in front of Sgr A is thus probably smaller than is thought by Little. Future observations should solve this problem.

Table 2

Flux of Sagittarius A at frequencies lower than 3000 MHz

Frequency (MHz)	Authority	Instrument	Flux (10^{-26} W m^{-2} Hz^{-1})	Notes
1670	Robinson *et al.* (1964)	Pencil-beam $12'.5$	360	*1*
1400	Kerr and Sinclair (1967)	Pencil-beam $13'.5$	405	*1*
	Lequeux (1962)	Interferometer	300	
	Rougoor (1966)	Interferometer	$\leqslant 150$	*2*
	Parijskij (1964)	Fan-beam $7'$	250	
960	Maltby and Moffet (1962)	Interferometer	$\leqslant 250$	
	Parijskij (1964)	Fan-beam $11'$	$\geqslant 350$	
408	Burke and Firor (1959)	Fan-beam $12'$	150	*3*
	Little (1966)	Fan-beam $1'.5$	385	
100	Sanamian	Interferometer	< 30	*4*
	Mills (unpublished)	Interferometer	undetected	

Notes: 1. Estimated by Downes and Maxwell (1966).
2. Private communication.
3. Quoted by Downes and Maxwell (1966).
4. Private communication via Parijskij.

From Little's observations it is difficult to derive the contribution of the *extended source* at 408 MHz; nevertheless one gets the impression that its total flux density is greater than at centimetre wavelengths, and that its dimensions are larger. Observations by Mills (1956, 1964) at 85·5 MHz ($\lambda = 3{\cdot}5$ m), with a resolution of $50'$, confirm this

impression. They show an extended source, whose dimensions are difficult to determine because the resolution is insufficient and the separation of the source from the background rather arbitrary; one may estimate dimensions of $3° \times 1°$, three times larger than those of the extended thermal source. The maximum brightness temperatures are 15 000 to 20 000 °K above the galactic ridge (in fact, they would be even higher if the absorption at the centre, of which we shall speak later, were absent); this shows that the extended source observed at these lower frequencies must be largely *non-thermal.* The isophote map by Mills indicates, at the centre of this source, a depression whose position corresponds to that of Sgr A. This absorption cannot be due to the small thermal sources which are prominent at centimetre waves, since they together cover much too small a solid angle; rather, the extended thermal source might be responsible. The latter, whose dimensions of $1°.0 \times 0°.4$ are comparable with those of Mills' aerial beam, has an optical thickness of about 2 at 85·5 MHz and can therefore virtually completely absorb the non-thermal radiation of regions situated beyond, as has already been suggested by Westerhout (1958). The absorption is much more prominent still in the maps at 19·7 MHz (Shain 1957; Shain *et al.* 1961), on which the galactic centre corresponds to a very deep depression.

These absorption phenomena make it impossible to determine the flux at metre wavelengths. In particular, the spectrum of the extended non-thermal component is unknown.

4. ASSOCIATION OF THE REGION OF SAGITTARIUS A WITH THE CENTRE OF THE GALAXY

It is highly probable that the whole of the structures described is situated at the galactic centre.

(1) The source *Sgr A* coincides, within the limits of error ($< 10'$ in both longitude and latitude), with the centre of symmetry of the Galaxy as determined by other means. If it is at a distance of 10 kpc, its linear diameter of 10 pc is similar to that of the optical nucleus of M 31.

(2) The *thermal extended structure* is also centred on the centre of symmetry of the Galaxy. The presence of ionized hydrogen in the central region is confirmed by observations of Courtès (1964), which have revealed two regions, located about 1° from Sgr A, where the Hα line is present with a very large radial velocity (−150 km/sec); such a velocity can only be associated with the centre of the Galaxy.

(3) The *small thermal sources* cannot be identified with the optical H II regions E 13, E 15, E 16, etc., which certainly lie in a rather nearby spiral arm (Courtès 1964). They are almost perfectly aligned on the galactic equator: their latitudes are all smaller than 10′, suggesting that they are at large distances from the Sun. Such a colinear configuration of small sources appears to be unique in the Galaxy; but the hypothesis (Drake 1959) that they would be disposed in a ring around Sgr A would seem rather artificial. The large radial velocities observed by Mezger and Höglund (1967), +59 km/sec for G 0·2 0·0 and −25 km/sec for G 0·7 0·0 (cf. the footnote on page 397.—*Editor*), cannot be due to differential rotation and therefore confirm that these two sources belong to the central region (see also Section 3*b* of Kerr's Paper 42).

(4P The association of Sgr A and of two galactic sources, G 0·7 0·0 and G − 0·6 − 0·1, with the central region is further confirmed by *observations in the 21-cm line* (Kerr

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Table 3

Physical data on the centimetre-wave sources in the galactic centre

Assumptions: distance $R_0 = 10$ kpc; $T = 10^4$ °K for thermal sources

Designation (Downes and Maxwell 1966)	Angular dimensions	Linear dimensions (pc)	Character *	$S(3000)$ **	Emission measure (cm^{-6} pc)	Density (cm^{-3})	Mass ($M_{\odot}$)
Sagittarius A	≈ 3′.5	10	NT $\alpha = 0.70$	300	—	—	—
Extended component	1° × 0°.4	170 × 70	T	600	0.4 × 10^5	15	720 × 10^3
	3° × 1°	500 × 170	NT	?	—	—	—
G −0.6 −0.1	5′ × 3′	15 × 9	T	17	1.5 × 10^5	100	4 × 10^3
G 0.1 0.0	7′ × 5′	10 × 15	T	70	2.5 × 10^5	120	15 × 10^3
G 0.2 0.0	17′ × 5′	50 × 15	T	170	2.5 × 10^5	120	32 × 10^3
G 0.5 0.0	8′ × 4′	23 × 12	T	50	2 × 10^5	100	12 × 10^3
G 0.7 0.0	5′ × 2′	15 × 6	T	60	8 × 10^5	300	6 × 10^3
G 0.9 0.1	5′ × 5′	15 × 15	T	13	0.7 × 10^5	70	6 × 10^3
G 1.1 0.1	6′ × 6′	17 × 17	T?	22	0.8 × 10^5	70	8 × 10^3
						Total	8 × 10^5

*T = thermal, NT = non-thermal.

**$S(3000)$ = flux density at 3000 MHz; units: 10^{-26} W m^{-2} Hz^{-1}

and Vallak 1967; see also Kerr, Paper 69 in this volume). The component at -50 km/sec corresponding to the 3-kpc arm appears in absorption in the whole region, and in particular in front of the three sources mentioned. Yet, one also finds absorption at positive velocities (more notably so in the OH-lines); this indicates, if these sources are at the centre of the Galaxy, the presence of motions of gas towards the centre; of course, the atter could not serve as an argument against the central location of these sources.

In the following we shall consider that the totality of the observed structures in the region of Sgr A is situated at the centre of the Galaxy. On the basis of this hypothesis, Table 3 summarizes the physical data concerning these objects.

5. ATTEMPTS AT INTERPRETATION

a. Sagittarius A

The striking similarity of the dimensions of Sgr A and the *optical nucleus of M 31* suggests that these objects are identical in nature. Unfortunately one can neither observe an optical nucleus of the Galaxy nor, for lack of resolution, the possible radio emission of the nucleus of M 31. The most recent radio observations (MacLeod 1964; Kraus *et al.* 1966) do not even allow the distinction of emission from the entire central region of M 31.

If the galactic nucleus, like that of M 31, is a very dense cluster of stars, it is not surprising that the radio source has dimensions analogous to the stellar nucleus of M 31. In fact the gas, and consequently the magnetic field, must be strongly coupled to the stars by the intense field of gravitation. The mass of the nucleus of M 31 is indeed considerable: the figure of $1{\cdot}3 \times 10^7\ M_\odot$ derived by Walker *et al.* (1960) from the rotation curve of the nucleus is a strong underestimate, since these authors have neglected the velocity dispersion of the stars, which is quite significant (Kinman 1965); a mass of $10^8\ M_\odot$ appears more probable. As the stellar nucleus is dynamically separate from the rest of the galaxy (see the rotation curve of the nucleus of M 31 measured by Walker *et al.* 1960), the same is probably true for the gas.

The spectrum of radio radiation of Sgr A being unknown below 3 GHz, it is difficult to estimate the *energy content* of the source by the classical method of equipartition between the magnetic energy and that of the relativistic particles. Downes and Maxwell (1966) have nevertheless given reasonable limits:

$$5 \times 10^{-5}\ \text{gauss} < H < 5 \times 10^{-4}\ \text{gauss}$$

$$3 \times 10^{48}\ \text{erg} < E_{\text{tot}} < 3 \times 10^{50}\ \text{erg};$$

these values correspond to a spectrum of the form $S(\nu) \sim \nu^{-0{\cdot}7}$ extending respectively from 1 to 10 GHz, or from 10 MHz to infinity. Although equipartition may not be realized, these coarse estimates allow an order-of-magnitude calculation of the *lifetime* of relativistic electrons against synchrotron and Compton losses; this lifetime cannot exceed 10^4 to 10^6 years. Either Sgr A is a temporary source, or it is maintained by continuous acceleration of relativistic electrons; the latter is entirely possible in a strongly turbulent medium where stellar collisions are not infrequent. These alternatives may be related to two possible hypotheses for the interpretation of the *outward motions of neutral hydrogen* in the central region of the Galaxy: an origin in one discrete event, or a continuous phenomenon. It is noteworthy that, if these motions have been caused by a

single explosion at the centre of the Galaxy, this event must have taken place 10 or 20 million years ago (Burbidge and Hoyle 1963, Lequeux 1963) and consequently cannot be the same which produced the relativistic electrons of Sgr A.

At any rate, the existence of the non-thermal source Sgr A demonstrates a temporary or permanent activity in the nucleus of the Galaxy.

b. Thermal components

It is of interest to compare the distributions of *ionized and neutral hydrogen* in the central regions of the Galaxy. The total mass of ionized hydrogen ($8 \times 10^5 M_\odot$, see Table 3) is only slightly smaller than that of neutral hydrogen ($3 \times 10^6 M_\odot$) contained in the rapidly rotating central disk of 750 pc radius (Rougoor 1964). The thickness of the extended thermal source (70 pc) is quite similar to the central thickness of the neutral-hydrogen disk, but its radius (85 pc) is much smaller; the hydrogen is probably completely ionized within this radius.

The complexity of the disposition of ionized gas is not surprising, in view of the tormented aspect of the distributions of neutral hydrogen and of OH molecules when observed with sufficiently high resolving powers (Kerr 1964, Bolton *et al.* 1964).

The *ionization* of the gas cannot be due to radiation of hot stars, as these are lacking in the central regions of galaxies of all types up to Sc; a thousand OB stars would be needed to ionize all the hydrogen. The same remark also applies to the ionized gas in the centre of M 31, for which Münch (1960) estimates an electron density of 50 cm^{-3} as compared with 15 cm^{-3} in the Galaxy; in the centre of M 31 there is no sign of the presence of any hot stars. It is tempting to ascribe the ionization to collisions with particles of moderate energies or to shock waves. However, Mezger and Höglund (1967) show that the electron temperature of the sources G 0·2 0·0 and G 0·7 0·0 (cf. the footnote on page 397.—*Editor*) probably is of the order of 6000 °K, which is incompatible with collisional excitation. In the end, therefore, radiative ionization appears more probable; according to Schmidt-Kaler (1966), it may be due to the nuclei of planetary nebulae, which must be quite abundant in the central regions.

c. Extended non-thermal component

This component is so poorly known that it would be premature to speculate about its origin. Nevertheless its energy content, for which Parijskij (1964) suggests the figure 3×10^{53} erg, certainly exceeds that of Sgr A, since the lifetime of relativistic electrons is here of the order of 10^6 to 10^7 years. Just as the central source, this component must either be temporary or be continually supported by relativistic electrons probably coming from the nucleus.

6. CONCLUSION

The recent observations, particularly those at centimetre wavelengths, have considerably clarified our knowledge of the continuous emission from the galactic centre. In particular, they have given definite proof that the radiation from the galactic nucleus is non-thermal. Still, a large amount of work remains to be done. Observations with resolutions better than 10′ (arc) throughout the decimetre and metre bands are required for a determination of the spectrum of Sgr A. Some observations of this kind are under way or planned for the near future (Owens Valley, Molonglo); also, a series of occultations

by the Moon observable from the northern hemisphere in 1967–70 will make it possible to gain better knowledge of the fine structure of these regions.

The study of the continuous emission of the galactic centre gives direct evidence for activity in the nucleus of the Galaxy. Further proof for this activity comes from the 21-cm line observations described by Kerr in this Symposium (Paper 42). One of the most striking observations is that by Shane at Dwingeloo (Oort 1967) of two clouds of neutral hydrogen with high velocities, which appear to be symmetrically ejected in directions away from the galactic plane. The kinetic energy involved in this phenomenon is about 10^{53} erg, that is, of the same order as the energy associated with the non-thermal radiation in the vicinity of the galactic centre.

REFERENCES

Baars, J. W. M., Mezger, P. G., Wendker, H. 1965, *Z. Astrophys.*, **61**, 134.

Barrett, A. H., Rogers, A. E. E. 1966, *Nature*, **210**, 188.

Biraud, F., Lequeux, J., Le Roux, E. 1960, *Observatory*, **80**, 116.

Blaauw, A., Gum, C. S., Pawsey, J. L., Westerhout, G. 1960, *Mon. Not. R. astr. Soc.*, **121**, 123.

Bolton, J. G., Gardner, F. F., McGee, R. X., Robinson, B. J. 1964, *Nature*, **204**, 30.

Broten, N. W., Cooper, B. F. C., Gardner, F. F., Minnett, H. C., Price, R. M., Tonking, F. G., Yabsley, D. E. 1965, *Austr. J. Phys.*, **18**, 85.

Burbidge, G. R., Hoyle, F. 1963, *Astrophys. J.*, **138**, 57.

Burke, B. F. 1965, *A. Rev. Astr. Astrophys.*, **3**, 275.

Clark, G., Garmire, G., Oda, M., Wada, M., Giacconi, R., Gursky, H., Waters, J. R. 1965, *Nature*, **207**, 584.

Cooper, B. F. C., Price, R. M. 1964, IAU Symposium, no. 20, *The Galaxy and the Magellanic Clouds*, Eds. F. J. Kerr and A. W. Rodgers, p. 168, Austr. Acad. Sci., Canberra.

Courtès, G. 1964, IAU Symposium, no. 20, *The Galaxy and the Magellanic Clouds*, Eds. F. J. Kerr and A. W. Rodgers, p. 199, Austr. Acad. Sci., Canberra.

Downes, D., Maxwell, A. 1966, *Astrophys. J.*, **146**, 653.

Downes, D., Maxwell, A., Meeks, M. L. 1965, *Nature*, **208**, 1189.

Drake, F. D. 1959, *Astr. J.*, **64**, 329; isophote map in Steinberg, J. L., Lequeux, J. 1963, *Radio Astronomy*, McGraw-Hill Book Comp., Inc., New York, p. 193.

Drake, F. D. 1966, Private communication.

Dravskih, A. F., Dravskih, Z. V., Turevskij, V. M., Solonikov, A. A. 1966, *Astr. Cirk. Izdav. bjuro astr. Soobšč. Kazan*, no. 354.

Haddock, F. T., Mayer, C. H., Sloanaker, R. M. 1954, *Astrophys. J.*, **119**, 456.

Hollinger, J. P. 1965, *Astrophys. J.*, **142**, 609.

Kellermann, K. I. 1964, *Publ. Owens Valley Radio Obs.*, **1**, 1.

Kerr, F. J. 1964, IAU Symposium, no. 20, *The Galaxy and the Magellanic Clouds*, Eds. F. J. Kerr and A. W. Rodgers, p. 187, Austr. Acad. Sci., Canberra.

Kerr, F. J., Sinclair, M. W. 1967, *Austr. J. Phys.*, in press.

Kerr, F. J., Vallak, R. 1967, *Austr. J. Phys. Astrophys. Suppl.*, No. 3, 1.

Kinman, T. D. 1965, *Astrophys. J.*, **142**, 1376.

Kraus, J. D., Dixon, R. S., Fisher, R. O. 1966, *Astrophys. J.*, **144**, 559.

Lequeux, J. 1962, *Ann. Astrophys.*, **25**, 221.

Lequeux, J. 1963, *Ann. Astrophys.*, **26**, 429.

Little, A. G. 1966, Private communication.

MacLeod, J. M. 1964, *Science*, **145**, 389.

McGee, R. X., Robinson, B. J., Gardner, F. F., Bolton, J. G. 1965, *Nature*, **208**, 1193.

Maltby, P., Moffet, A. T. 1962, *Astrophys. J. Suppl. Ser.*, **7**, 141.

Maxwell, A., Downes, D. 1964, *Nature*, **204**, 865.
Mezger, P. G., Henderson, A. P. 1967, *Astrophys. J.*, **147**, 471.
Mezger, P. G., Hoglund, B. 1967, *Astrophys. J.*, **147**, 490.
Mills, B. Y. 1956, *Observatory*, **76**, 65.
Mills, B. Y. 1964, *A. Rev. Astr. Astrophys.*, **2**, 185.
Münch, G. 1960, *Astrophys. J.*, **131**, 250.
Oort, J. H. 1967, IAU Symposium, no. 29 (in press).
Parijskij, Ju. N. 1959, *Dokl. Akad. Nauk SSSR*, **129**, 126; *Soviet Phys. Dokl.*, **4**, 1172.
Parijskij, Ju. N. 1964, IAU Symposium, no. 20, *The Galaxy and the Magellanic Clouds*, Eds. F. J. Kerr and A. W. Rodgers, p. 172, Austr. Acad. Sci., Canberra.
Piddington, J. H., Minnett, H. C. 1951, *Austr. J. scient. Res.*, **A4**, 459.
Robinson, B. J., Gardner, F. F., Van Damme, K. J., Bolton, J. G. 1964, *Nature*, **202**, 989.
Rougoor, G. W. 1964, *Bull. astr. Inst. Netherl.*, **17**, 381.
Rougoor, G. W. 1966, Private communication.
Schmidt-Kaler, Th. 1966, Private communication.
Shain, C. A. 1957, *Austr. J. Phys.*, **10**, 195.
Shain, C. A., Komesaroff, M. M., Higgins, C. S. 1961, *Austr. J. Phys.*, **14**, 508.
Tolbert, C. W., Straiton, A. W. 1965, *Astr. J.*, **70**, 177.
Walker, M. F., Lallemand, A., Duchesne, M. 1960, *C. r. hebd. Séanc. Acad. Sci.*, Paris, **250**, 975 (also in: Lallemand, A., Duchesne, M., Walker, M. F. 1960, *Publ. astr. Soc. Pacific*, **72**, 76).
72, 76).
Westerhout, G. 1958, *Bull. astr. Inst. Netherl.*, **14**, 215.

NOTE ADDED IN PROOF

E. E. Becklin and G. Neugebauer have recently observed radiation from the galactic nucleus at 1.65, 2.2, and 3.4 microns, thus confirming its identity with the nucleus of M 31 (*Sky and Telescope*, April 1967).

E. C. Reifenstein III, T. L. Wilson, B. F. Burke and P. G. Mezger have detected the 109α-hydrogen line in five of the seven most intense sources of the galactic center, the exceptions being Sgr A and G 0·2 0·0. 109 α-line emission attributed by Mezger and Höglund (1967) to G 0·2 0·0 and G 0·7 0·0 comes in fact (due to a pointing error) from G 0·7 0·0 and G 1·1 − 0·1 respectively (*American URSI Spring Meeting*, Ottawa, 23-25 May 1967).

Discussion

L. Biermann: Could there be an analogue to Sgr A in M 31? Are there any observations bearing on this point?

J. Lequeux: No emission from the central region of M 31 has yet been detected. This is not really surprising, as the emission of the central regions of our Galaxy would just be at the limit of detection with existing instruments, if these regions were at the distance of M 31.

I.A.U. Symposium no. 31, 1967

69. OBSERVATIONS OF THE CONTINUUM NEAR THE GALACTIC CENTRE

F. J. KERR*

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A continuum survey of the galactic-centre region has been carried out at Parkes at 20 cm wavelength over the area $l^{II} = 355°$ to $5°$, $b^{II} = -3°$ to $+3°$ (Kerr and Sinclair 1966, 1967). This is a larger region than has been covered in such surveys in the past. The observations were done as declination scans.

In addition to the main ridge, located approximately along the galactic equator, the contour diagram shows two shorter ridges running out in opposite directions at a steep angle to the equator (cf. Figure 7 in Paper 42). These ridges could well be associated with jets of matter ejected from the vicinity of the centre. The whole pattern of the ridgelines, including the inclined ridges and the details of the equatorial ridge, is highly symmetrical about the position of Sagittarius A. The intensity levels are not so symmetrical, but the ridgeline pattern shows a higher degree of symmetry than is found in any other aspect of the galactic-centre observations so far.

Hydrogen-line absorption observations can give information about the relative positions of the various components of the complex continuum source in the direction of the centre. There have been various suggestions in the past that one or other of these components may not be as far away as the centre. Recent observations at Parkes (Kerr and Vallak 1967) indicate that all of the main components show absorption at the velocity of the 3-kpc arm. If this is so, they must all be further away from us than the 3-kpc arm, and thus are presumably near the centre.

REFERENCES

Kerr, F. J., Sinclair, M. W. 1966, *Nature*, **212**, 166-167.
Kerr, F. J., Sinclair, M. W. 1967, *Austr. J. Phys.*, in press.
Kerr, F. J., Vallak, R. 1967, *Austr. J. Phys. Astrophys. Suppl.*, no. 3, 1-27.

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I.A.U. Symposium no. 31, 1967

70. DISCUSSION ON THE GALACTIC NUCLEUS

(This discussion was opened with an invited contribution by Dr Pikel'ner)

S. B. Pikel'ner:

It is a difficult task to open the theoretical discussion on a subject about which we have so many complicated observations and no theory. I will restrict my comments to two general questions: What is the source of the kinetic energy and the energy of cosmic rays, and how is this energy transmitted to the gas?

Observations show that the motions in the central disk ($R \approx 100$ pc) are neither pure rotation nor pure expansion; therefore, the dissipation of kinetic energy should be due to shocks. The time-scale of dissipation is about 10^7 years and the energy store about 10^{51} erg. If the observed motions are permanent, the energy source should yield 10^{54} erg over a time-span of 10^{10} years. The energy of cosmic rays in the central region is 10^{52} to 10^{53} erg. If the time-scale for escape is 10^7 to 10^8 years, and the presence of cosmic rays is assumed permanent, one finds that a total energy supply of more than 10^{54} erg is needed.

The energy of infalling gas and of the differential rotation of the gas in the central region is insufficient, unless the gas contracts into objects of rather high density. There should, therefore, in the centre of the Galaxy be a nucleus much smaller than Sagittarius A. The transmission of energy from this body may be due to winding-up of the magnetic field lines and to the pressure of cosmic rays; both these factors may lift the gas, and its falling back to the galactic plane along the magnetic lines may maintain the random motions. Another possible mechanism is the ejection of gas from the nucleus. An example of such ejection may be the bar with a velocity of about 250 km/sec which was mentioned by Kerr in Paper 42. This ejection must have occurred about ten million years ago, and there are no other strong jets in the central region. This may be an argument in favour of a series of explosions but not of permanent activity.

Not all the mass in the central region can have been ejected from the nucleus, as the gas has angular momentum. Part of this gas may be the remnant of infalling gas. The mass of the infalling gas may be not large, since the outflow of gas from the central region is not large either. The 3-kpc Arm is moving outward, but its velocity is not very high and after some time it will turn back.

The importance of galactic nuclei and of their activity was first stressed by Ambarcumjan. He proposed that there might be a superdense body in the centre of a galaxy, and that expulsion of matter from this body might lead to formation of stars and of the stellar system. I do not agree with such an interpretation. The majority of astronomers believe that the central body appears as a collapsing mass such as was proposed by Hoyle and Fowler. There were some discussions about this at the recent Bjurakan symposium (IAU Symposium no. 29) and I will summarize them here. The latest model for the central body, according to Layzer and, especially, to papers by Ozernoj, is in quasi-equilibrium. It is a gas cloud slowly condensing in a strong magnetic field. The equilibrium is not stable and turbulence develops, supported by gravitational energy. Circulation and ejection of matter, and production of cosmic rays, take place in this model. Sagittarius A may be a kind of magnetic halo around such a central body.

Explosions occur when a sufficient mass of infalling gas has accumulated. It is possible that the power of the explosions depends on the rate of accumulation of the gas.

T. K. Menon:

The dimensions of the Sagittarius A source are about 10 pc. Pikel'ner mentions velocities of expansion of 250 km/sec and time-scales of 10^7 years in interpreting the 3-kpc Arm. Where did the expansion start from? How is it related to the Sgr A source? Has the source been constant in size during the 10^7 years? Or is the time-scale of the source much shorter? I think we have a number of inter-related problems here, which should be solved together in an attempt to form a coherent picture of the physical processes occurring in the nuclear regions of our Galaxy and of other galaxies.

Pikel'ner:

The expansion of the bar should have started from the nucleus. The size of 6 pc for Sgr A refers to the magnetic region (halo), not to the nuclear body. This body may be 10^{15} or 10^{16} cm in size, and it may be a gas which is supported by magnetic pressure. Such a picture was suggested by Layzer and, independently and in a more elaborate way, by Ozernoj. The time-scale of 10^7 years mentioned by me is the time of propagation of the shock to the distance of the 3-kpc Arm; it may also be the interval between explosions. For the explosion itself the time-scale is much shorter.

I. S. Šklovskij:

If the spectrum of Sgr A is non-thermal at low frequencies, the change of spectral index at 2000 MHz may be caused by synchrotron losses, like in the Crab Nebula. In this case, if $H \approx 3 \times 10^{-4}$ gauss, the age of the source is about 10^6 years, and the production of relativistic particles may continue throughout the life of the source.

Ju. N. Parijskij:

I think that this explanation cannot be applied to the central source, because the decrease in the flux is too large.

M. S. Roberts:

Lequeux pointed out the large amount of ionized hydrogen contained in the several thermal sources in the region of Sagittarius A. I should like to call attention to the fact that there are, otherwise normal, spiral galaxies which have numbers of giant H II regions in their nuclear parts. An outstanding example is NGC4321. Other such spirals are listed in the notes to Morgan's galaxy catalogues (*Publ. astr. Soc. Pacific*) as systems containing 'hot spots' in their nuclei.

E. M. Burbidge:

While all irregular galaxies, most Sc's, and some Sb systems show an emission-line spectrum emitted by ionized gas in their nuclear regions which indicates that the excitation and ionization conditions are the same there as they are in spiral-arm regions, a few Sc systems, some Sb's, and virtually all So and E galaxies that have nuclear H II regions show something very different. The intensity ratio of the Hα and [N II] λ6583 lines changes from about 3 (the spiral-arm value) to something much less than unity. This can be explained by a higher electron temperature in the nuclear region, but the question remains how to maintain this. Possibly one is seeing a small-scale phenomenon like that in radio galaxies, but the frequency of the phenomenon in the centre of those galaxies

which have a large K-giant stellar population suggests rather that it has something to do with these stars. Collisions between gas clouds ejected by evolving stars, or ejection of more energetic solar-wind type particles, have been considered.

D. Lynden-Bell:

Osterbrock and Parker have suggested that collisions of many small clouds give the phenomena associated with Seyfert galaxies. I suggest that the same phenomenon on a smaller scale may be responsible for what you observe in M51. Perhaps the clouds hold themselves together by gravity and only occasionally hit one another.

E. M. Burbidge:

This also might be a possibility.

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Chapter III D

Cosmic Rays in the Galaxy

CHAIRMAN: H. Alfvén

(*Klungliga Tekniska Högskolan, Stockholm, Sverige*)

'*I hope during my lifetime to see the full victory of the galactic theory.*'
'*I hope you will live very long.*'

V. L. Ginzburg and H. Alfvén
in the Discussion (Paper 74)

71. COSMIC RAYS IN THE GALAXY
(Introductory Report)*

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ABSTRACT

A summary is presented of our knowledge concerning the properties and origin of cosmic rays observed near the Earth. We discuss different conceptions of the origin of cosmic rays, including both galactic and metagalactic origins, and their relation to galactic structure. Our arguments favour a galactic rather than a metagalactic origin.

1. INTRODUCTION

At present there is no doubt that cosmic rays play a prominent role in the Universe and, in particular, in our Galaxy. The two most important parts of this role are the following. First, the acceleration of particles is a universal process taking place almost everywhere: in the radiation belts of the planets, in the solar atmosphere, in supernova shells, in radiogalaxies, in quasars, and so on. Second, the energy density of the cosmic rays, w_{cr}, and their pressure, $p_{cr} = w_{cr}/3$, in a number of situations are believed to be a major, and even decisive, factor in energetics and dynamics.

In addition to the direct data concerning cosmic rays near the Earth, we have information of predominantly radio-astronomical character about the electron component of cosmic rays in supernova shells, galaxies and radiogalaxies. Electrons and positrons are completely equivalent as emitters of synchrotron radiation, and in some other respects. Therefore, we shall not distinguish the positron component of cosmic rays from the negative electrons except where necessary to avoid misunderstanding.

* The present text contains a few additions and changes to the preprint distributed in Russian at the Symposium.

The origin of the cosmic rays observed near the Earth cannot yet be regarded as finally established. This very problem may be considered as the central one. There are two possibilities. The galactic theory believes that the main part of the cosmic rays observed near the Earth originate in our Galaxy. The metagalactic theory proceeds from the assumption that the cosmic rays have their origin mainly in the Metagalaxy (say, in radiogalaxies and quasars) and penetrate the Galaxy from outside. In discussing these theories for the origin of the main part of the cosmic rays, we shall consider only particles with energies E less than 10^{15} to 10^{17} eV. For particles with greater energies, a metagalactic origin seems probable from every point of view.

In our own opinion, for particles with $E < 10^{15}$ to 10^{17} eV, all the known considerations testify in favour of the galactic theory (Ginzburg and Syrovatskij 1964, 1966*a*, 1966*b*). However, the metagalactic theory also has its supporters (Burbidge and Burbidge 1966). The most important point is that the galactic theory cannot yet be considered as proved. The main uncertainty in this connection is the structure of the galactic halo and its magnetic fields.

We consider it our task to set forth, as objectively as possible, the present state of the problem concerning the origin of the cosmic rays in the Galaxy. For this purpose we shall first review the available data about cosmic rays near the Earth, since this information is not easily accessible to the majority of astronomers. We shall not touch upon the radio-astronomical data, as these are discussed by Baldwin (Paper 56). Further, we shall present and discuss the evidence against the metagalactic theory. In conclusion, we shall indicate further possibilities for proving or disproving the galactic and metagalactic models.

2. COSMIC RAYS NEAR THE EARTH

In the following review of data concerning cosmic rays near the Earth, we shall especially consider their intensity, chemical composition, energy spectrum, and isotropy, and the electron-positron component. For more details, see Ginzburg and Syrovatskij (1964), Stickland (1966) and Webber (1967).

(*a*) *Intensity*

The total intensity of the galactic cosmic rays observed near the Earth varies strongly (by a factor 4 or 5) during the eleven-year period of solar activity. These changes are due to the conditions for propagation of cosmic rays in interplanetary space and refer, mainly, to the particles of small energies. The intensity of particles having a rigidity $P \equiv cp/Ze$ (p = momentum, Ze = charge) exceeding 2·3 GV (for protons this corresponds to a total energy $E > 2{\cdot}5$ GeV) varies from minimum solar activity (1954–55 and 1965) to maximum (1958) by not more than 40%. For $P > 4{\cdot}5$ GV, corresponding to a total energy $\epsilon > 2{\cdot}5$ GeV/nucleon for nuclei having $A = 2Z$, the variations do not exceed 30%.

We will use the data obtained during the *minimum of solar activity*, when the total intensity of cosmic rays observed near the Earth, as well as those of individual components, are closest to their galactic values, i.e. to the intensities outside the solar system. The magnitude of the residual modulation during minima of solar activity is not yet reliably established; according to certain estimates, it does not exceed 30 to 50% for particles with $P \geqslant 2{\cdot}5$ GV.

Bearing in mind these reservations, one finds for the *total intensity* of galactic cosmic rays (we mean particles having kinetic energies $\epsilon_k > 100$ MeV/nucleon):

$$I_{cr} \approx 0{\cdot}3 \text{ particles cm}^{-2} \text{ sec}^{-1} \text{ sr}^{-1}. \tag{1}$$

Approximately 15% of this intensity is supplied by helium nuclei, and about 1·5% by nuclei having $Z > 2$; the rest is in protons. More detailed data about the chemical composition we shall quote below. We now present values for the total *particle density*:

$$n_{cr} \approx 1{\cdot}6 \times 10^{-10} \text{ particles cm}^{-3}, \tag{2}$$

and for the *energy density*:

$$w_{cr} \approx 0{\cdot}6 \text{ eV cm}^{-3} \tag{3}$$

of galactic cosmic rays in the neighbourhood of the solar system. Direct data about cosmic rays in distant regions of the Galaxy are lacking, if one does not consider the electron component. However, it is natural to assume that the values quoted in (1)–(3) are close to the mean with respect to the total volume of the Galaxy (see Section 4).

(*b*) *Chemical composition*

It is convenient to consider the *nuclear* (*chemical*) *composition* of cosmic rays for particles having the same velocity or, which is equivalent, the same energy per nucleon. The most detailed data (Webber 1967) are available for the range of energies $\epsilon \geqslant 2{\cdot}5$ GeV/nucleon, which corresponds to rigidities $P \geqslant 2{\cdot}3$ GV for protons and $P \geqslant 4{\cdot}5$ GV for nuclei with $A = 2Z$. These data are given in Table 1, where the nuclei with $Z > 2$ are combined into groups defined by atomic numbers Z. The table also presents the distribution of elements in the Universe according to Suess and Urey (1956) and to Cameron (1959).

Table 1

Abundances of elements in cosmic rays and in the Universe

Group of nuclei	Atomic number	Intensity* for energies above 2·5 GeV/nucleon	Number of nucleons in flux	Abundance relative to H-nuclei	Abundance in the Universe
P	1	1300 ± 100	1300	650	3360–6830
α	2	94 ± 4	376	47	258–1040
L	3–5	2·0 ± 0·3	20	1	10^{-5}
M	6–9	6·7 ± 0·3	94	3·3	2·64–10·1
H	⩾ 10	2·0 ± 0·3	62	1	1
LH	10–14	1·4 ± 0·40	34	0·68	0·89–0·79
MH	15–19	0·1 ± 0·1	2	0·06	0·05–0·16
VH	⩾ 20	0·5 ± 0·2	25	0·26	0·06–0·05

* Unit: particles m^{-2} sec^{-1} sr^{-1}

Analysis of the chemical composition in Table 1 leads to the following conclusions.

(*i*) The *L-nuclei* (Li, Be, B), whose abundance in the Universe is negligibly small, are present in great quantities in cosmic rays. This fact can be explained either by quite exotic properties of the cosmic-ray sources or, which is more probable, by the appearance

of L-nuclei as a result of fragmentation of M- and H-nuclei during their travel through interstellar space. In the latter case the cosmic rays must, on the average, penetrate through a *thickness* x of about 3 g/cm^2 of interstellar gas* (that is, 3 gram of gas per column of 1 cm^2 cross-section) before reaching the Earth. This very important conclusion makes it possible to estimate the mean *age* of the observed cosmic rays:

$$T_{cr} = x/\rho c \approx 2 \times 10^6/n \approx 2 \times 10^8 \text{ years,} \tag{4}$$

where we have taken $\rho = 2 \times 10^{-26}$ g cm^{-3}, $n = 10^{-2}$ atoms cm^{-3} as mean density of the interstellar gas.

(*ii*) Protons and helium nuclei are less abundant, relative to heavy nuclei, in cosmic rays than in the Universe on the average. In other words, there is a considerable excess of *heavy nuclei.* Within the group H of heavy nuclei we note a similar effect: the heaviest nuclei ($Z \geqslant 20$) are about 5 times overabundant with respect to group H as a whole. This can be explained either by a very specific chemical composition of the gas in the sources, or by a selective acceleration mechanism, favouring the acceleration of the heavier elements.

(*iii*) A quite notable gap is observed in the region of *MH-nuclei.* This gap is evidence for the practically complete absence of nuclei with $Z = 15$ to 19 in the composition of the cosmic-ray sources, if one takes into account the production of such nuclei during fragmentation of heavier ones. The data about the MH-nuclei in cosmic rays are not very reliable, and estimates by various authors of the universal abundance of these nuclei differ by factors of 3 or 4. However, the values quoted suggest that in the near future one may be able, perhaps, to solve this problem of the abundance of MH-nuclei in cosmic-ray sources. If, for example, the MH-nuclei are in fact absent, a special explanation would be required, since nuclei of the M-group and the VH-subgroup are present in the sources.

The corollaries from a more detailed examination of the chemical and isotopic composition also are of great interest. They are as follows:

(*iv*) In the cosmic rays there is a considerable *excess of even nuclei* (even Z) with respect to odd ones; for instance, for the VH-group the ratio of abundances between odd and even equals, approximately, 0·08. In spite of the fact that this ratio is significantly greater than that for the universal abundances ($< 0{\cdot}01$), it is not sufficiently great to consider that the VH-nuclei passed through a thickness much exceeding their nuclear pathlength (about 2·5 g/cm^2). In the latter case, as a result of fragmentation, establishment of an 'equilibrium' distribution would be expected, with a ratio of odd to even nuclei of about 1/3. The absence of precise data on the fragmentation cross-sections prevents us from considering this conclusion as final, but it agrees well with other determinations of the thickness of matter penetrated, $x \approx 3$ g/cm^2 (see (*i*) above).

(*v*) The presence of a notable quantity of the *helium isotope* ^{3}He in cosmic rays [in the energy range 80 to 360 MeV/nucleon, $^3\text{He}/(^3\text{He} + {}^4\text{He}) \approx 0{\cdot}1$ to $0{\cdot}2$] allows an independent estimation of the thickness x, if one assumes that ^{3}He is absent in the sources. Comparisons between the thickness so obtained and that determined from the L-nuclei yield conclusions about the model of propagation of the cosmic rays. Namely, if in the relativistic region ($\epsilon_k \geqslant 1$ GeV/nucleon) the ratio $^3\text{He}/(^3\text{He} + {}^4\text{He})$

* A fraction of this thickness is passed in the source itself. We believe, however, on the basis of estimates for supernova envelopes, that this fraction is small.

exceeds 0·15, this supports the diffusion model (Kuževskij and Syrovatskij 1965). Preliminary results (Agrawal *et al.* 1966) favour the diffusion, as against the regular model (the diffusion model deals with an average of the thickness x, the regular model uses a fixed value for x).

(*vi*) Measurement of the *ratio* Be/B allows us to estimate the age of cosmic rays, after allowance for the probability of formation of these elements during fragmentation and radioactive decay $^{10}\mathrm{Be} \rightarrow {}^{10}\mathrm{B} + e^-$, for which the life-time $T_{1/2} = 4 \times 10^6\ \gamma_L$ years ($\gamma_L = E/Mc^2$ is the Lorentz factor). According to Daniel and Durgaprasad (1966), the age of cosmic rays is

$$T \geqslant 5 \times 10^7 \text{ years,}$$

and the mean concentration of interstellar gas in the region occupied by cosmic rays is

$$n = x\,(2 \times 10^{-24}\,c\,T)^{-1} \leqslant 0{\cdot}03 \text{ atom/cm}^3,$$

in good agreement with the values accepted previously (Ginzburg and Syrovatskij 1964).

(*vii*) There are no experimental indications of *variations* in the chemical composition with energy, over the whole range from 1·5 GeV/nucleon to 10^5 or 10^6 GeV/nucleon. However, at the lower non-relativistic energies the composition seems to be different. The ratio L/M increases from $0{\cdot}30 \pm 0{\cdot}02$ at relativistic energies to 0·5 at energies $\epsilon_k \approx 200$ to 400 MeV/nucleon. In this range of energies the influence of ionization losses is already appreciable, and the ordinary calculations of the penetrated thickness become unsuitable. Nevertheless, the increase of the ratio L/M poses difficulties for hypotheses placing the origin of the cosmic rays in a single explosion, which could have occurred, for instance, in the region of the galactic nucleus or in a nearby radio-galaxy. In this case the thickness, $x = \rho\, v\, T$, of matter penetrated during the time T after the explosion would be less for the non-relativistic particles than in the relativistic region; consequently, the quantity of non-relativistic L-nuclei would be much less than that of relativistic ones.

We have mentioned only the most important conclusions following from investigations of the chemical composition. Further data about the chemical and isotopic composition of cosmic rays should help to clarify their origin.

(*c*) *Energy spectrum*

An important feature of the primary cosmic rays is their energy spectrum. As was said above, the chemical composition of cosmic rays is constant in the energy range $\epsilon > 1{\cdot}5$ GeV/nucleon; therefore, the spectra for components with different charges are each proportional to the spectrum of the total radiation. In the energy range 10 GeV $< E < 10^6$ GeV this spectrum is well approximated by the expression:

$$I_{cr}\,(E > E_0) = 1{\cdot}7\, E_0^{-(\gamma-1)} \text{ particles cm}^{-2}\text{ sec}^{-1}\text{ sr}^{-1}, \tag{5}$$

with $\gamma = 2{\cdot}6$, where the energy E is expressed in GeV. It is not excluded that the *spectral index* γ in (5) changes slowly within the indicated range of energies. For energies $E \approx 10$ GeV the value $\gamma = 2{\cdot}5$ is more reasonable.

We stress that the spectrum (5) is valid for the *total* energies of the particles (nuclei). If one turns from the composition for particles at a given energy per nucleon (Table 1) to the composition for particles with a given total energy per nucleus, the protons amount

to about 40%, the helium nuclei to about 30%, and the nuclei with $Z > 2$ to about 30% of the whole intensity given in equation (5).

The spectrum changes its pattern in the energy range $E > 3 \times 10^{15}$ eV: it steepens to an index $\gamma = 3{\cdot}2 \pm 0{\cdot}1$. The cause of this 'break' is not yet clear, though it is probably produced by the faster diffusion of particles with $E \gtrsim 3 \times 10^{15}$ eV out of the Galaxy into intergalactic space. There are indications of a decrease of the spectral index to $\gamma \approx 2{\cdot}6$ for $E \gtrsim 10^{18}$ eV. This could be interpreted as a transition to metagalactic cosmic rays having a more or less uniform distribution in the Metagalaxy.

The spectral index gradually diminishes with E in the energy range $E < 10$ GeV; the maximum in the spectrum is observed at the rigidity $P \approx 1$ GV, beyond which the intensity falls rapidly. The shape and the position of the maximum significantly depend on solar activity. It is probable that outside the solar system the maximum in the spectrum at these energies is, in general, absent. Unfortunately, the determination of a precise shape for the spectrum of galactic cosmic rays in the range of small energies is still very difficult.

(*d*) *Isotropy*

The cosmic rays are isotropic to a high degree. There is as yet no sufficiently reliable evidence of any real anisotropy of galactic cosmic rays. Up to energies $E \approx 10^{15}$ eV any existing anisotropy does not exceed a few tenths of a per cent. (Preliminary data indicate an anisotropy amounting to a fraction of a per cent, with the predominant flow of cosmic rays directed away from the galactic centre. Because this result is of great importance, and at the same time unreliable, one ought to confirm it as soon as possible.)

(*e*) *The electron component*

We finally consider the electron component of cosmic rays. Recent experimental investigations have appreciably clarified this problem, which is of great importance to the astrophysics of cosmic rays and to radio astronomy. It has been established that the electrons amount to about 1·5% of the composition of cosmic rays, at energies $E_k \gtrsim 1$ GeV. In the energy interval 2 to 10 GeV, the spectrum of electrons has the form:

$$I_e(E) \approx 5 \times 10^{-3} E^{-2} \text{ electrons cm}^{-2} \text{ sec}^{-1} \text{ sr}^{-1} \text{ GeV}^{-1}. \tag{6}$$

Since the results of various authors are discrepant (Stickland 1966), the spectrum (6) should for the present be considered only tentative*. It is in agreement with data concerning the radio-emission of the halo, provided one assumes the strength of the magnetic field to be $H \approx 3 \times 10^{-6}$ gauss, and the halo to be quasi-spherical with a radius $R \approx 15$ kpc. [When comparing the calculated spectrum with the observed one, we used (Ginzburg and Syrovatskij 1964, Section 17) the data about the intensity of

* The spectrum communicated at the Symposium by Y. Tanaka (Paper 74) has, in the range 3 GeV < E < 30 GeV, the form

$$I_e(E) \approx 6 \times 10^{-3} E^{-2{\cdot}4} \text{ electrons cm}^{-2} \text{ sec}^{-1} \text{ sr}^{-1} \text{ GeV}^{-1}.$$

At $E < 3$ GeV it becomes flatter. It is not clear whether this break in the spectrum is due to solar modulation, or if it exists also in interstellar space and then is possibly due to synchrotron and Compton losses of the electrons (see Ginzburg and Syrovatskij 1964, Section 17).

In the range 2 GeV < E < 10 GeV the spectrum (6) is not contradicted by new experimental data.

non-thermal radio-emission, averaged over the hemisphere around the galactic anticentre. This intensity appears to be approximately 2·5 times higher than it is in the direction of the galactic pole. This seems to be explained by the contribution of the radio-emission of the disk. If one uses an intensity of 110 °K at ν = 178 MHz in the direction of the galactic pole, the electron distribution described by (6) will produce the observed radio-emission for $H \approx 3 \times 10^{-6}$ gauss over a distance of 10 to 15 kpc.]

In expression (6) the index of the electron spectrum, $\gamma_e \approx 2$, is smaller than the index of the differential spectrum of cosmic rays, which amounts to $\gamma \geqslant 2{\cdot}5$ at $E >$ 2 GeV. The spectrum of secondary electrons must be steeper than the proton spectrum, because of synchrotron and Compton losses. This fact, in combination with the indices reported, rules out that the electrons in the Galaxy would be secondaries, resulting from nuclear interactions of cosmic rays in the interstellar medium. Direct calculations of the expected intensity of radio-emission (Ginzburg and Syrovatskij 1964) confirm this conclusion. It is further proved by the proportion of positrons in the electron component; this proportion does not exceed 20% in the energy range $E > 5$ GeV. A reliable determination of the fraction of positrons will allow an assessment of the role of secondary electrons in the galactic radio-emission, and in addition supply independent data about the frequency of nuclear collisions and the age of the cosmic rays in the Galaxy.

3. REVIEW OF THEORIES (MODELS) FOR THE ORIGIN OF COSMIC RAYS

Where does the main part of cosmic rays reaching the Earth originate and what volume does it occupy? This is the basic question which we shall now try to answer. In this connection the term 'main part' of cosmic rays excludes from consideration the particles of solar origin, which play a role at energies below 1 to 3 GeV, as well as the particles of energies exceeding 10^{15} eV. We shall discuss the majority of particles in the energy range 10^9 eV $\lesssim E \lesssim 10^{14}$ to 10^{15} eV. If one does not consider hypotheses which are now only of historical importance (for instance, hypotheses about a solar origin of most of the cosmic rays), one may discuss the theories (or, more exactly, models) of the origin of cosmic rays indicated in Figure 1. A dividing line surely lies between

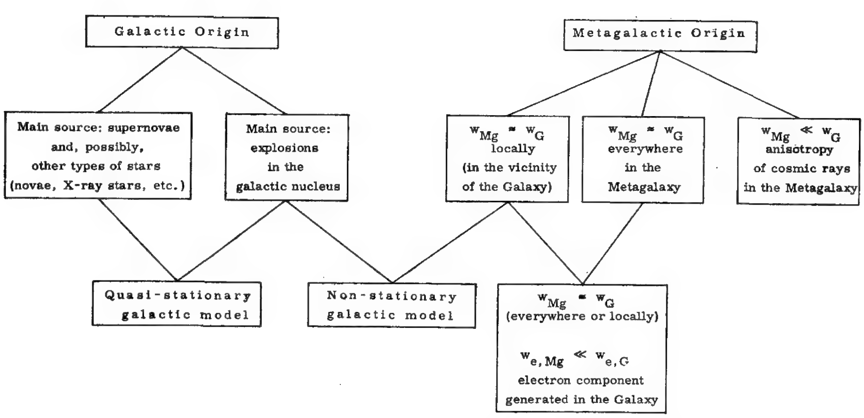

FIG. 1. Models for the origin of cosmic rays observed near the Earth.

the galactic and metagalactic models, but within the framework of these models several variants are available; we shall deal with these in more detail in Sections 4 and 5. First we define the notions occurring in Figure 1. The average energy density of cosmic rays in the Galaxy is designated by w_{G}. The energy density of the electron component of cosmic rays in the Galaxy is $w_{\mathrm{e,G}}$. The energy densities of cosmic rays and of their electron component in metagalactic space are, respectively, designated as w_{Mg} and $w_{\mathrm{e,Mg}}$.

4. GALACTIC THEORIES OF ORIGIN OF THE COSMIC RAYS

The galactic models postulate, as was pointed out in Section 1, that the main part of cosmic rays observed near the Earth is formed within the Galaxy. To specify the model one must indicate: the sources of the cosmic rays, the changes with time of their intensity (quasi-stationary or non-stationary models), and the region of the Galaxy occupied by them (disk or halo).

(*a*) *Specification of a model*

To save space we should note that we are inclined to consider the halo variant of a galactic model the most natural and probable. We may further specify this model as follows.

(*i*) The cosmic rays occupy a large volume, $V = 4/3\pi R^3 \approx (1 \text{ to } 5) \times 10^{68}\ \mathrm{cm}^3$, where $R = (3 \text{ to } 5) \times 10^{22}$ cm is the radius of the halo. Within this volume, containing both halo and disk, the cosmic rays become rather well-mixed on a time scale T of $(1 \text{ to } 3) \times 10^8$ years. Their energy density is practically constant, being (cf. equation (3)) of the order

$$w_{\mathrm{G}} \approx 10^{-12}\ \mathrm{erg/cm^3}. \tag{7}$$

(*ii*) The intensity of cosmic rays remains approximately the same during their life-time in the Galaxy, i.e., the model under discussion is quasi-stationary. This life-time, $T = (1 \text{ to } 3) \times 10^8$ years, is governed by leakage of particles from the system. (Within the framework of the diffusion approximation, $T \approx R^2/2D \approx 10^{16}\ \mathrm{sec} = 3 \times 10^8$ years for $R = 3 \times 10^{22}$ cm and a diffusion coefficient $D = l\,v/3 \approx 10^{29}\ \mathrm{cm^2/sec}$; the speed of cosmic rays along the magnetic field lines is $v \approx 10^{10}$ cm/sec and the effective free path is $l \approx 3 \times 10^{19}\ \mathrm{cm} = 10$ pc.)

(*iii*) The basic sources of cosmic rays are believed to be the explosions of supernova stars (besides the soft particles of solar origin, and the particles of energy $E > 10^{15}$ to 10^{17} eV, which may come from metagalactic space). However, it is thought possible that small explosions in the galactic nucleus, and perhaps novae, may make considerable contributions; for details see below.

The total energy of cosmic rays in such a model is:

$$W = w_{\mathrm{G}}\, V \approx 10^{56}\ \mathrm{erg} \tag{8}$$

(Formally, with the values indicated for V and w_{G}, the energy is $W \approx (1 \text{ to } 5) \times 10^{56}$ erg, but we think estimate (8) to be more reliable.)

The power of the sources, provided the cosmic-ray intensity is quasi-stationary, is:

$$U = W/T \approx 10^{40}\ \mathrm{erg/sec}, \text{ for } T \approx 10^{16}\ \mathrm{sec}. \tag{9}$$

For the electron component:

$$W_e \approx (1 \text{ to } 3) \times 10^{54} \text{ erg}, \; U_e = W_e/T_e \approx 3 \times 10^{38} \text{ erg/sec.} \tag{10}$$

Here we have made allowance for the fact that the mean lifetime for electrons, T_e, is somewhat less than that of the proton-nucleus component, on account of synchrotron and Compton losses. Because of these losses the electron energy E decreases by a factor 2 in a time $T_{e,m} \approx 3 \times 10^7 (H^2/8\pi + w_{ph})^{-1} mc^2/E$, where H is the strength of the magnetic field and w_{ph} is the energy density of photons; for $H^2/8\pi + w_{ph} \approx 10^{-12}$ erg/cm^3, the time is $T_{e,m} \approx 3 \times 10^{15}$ sec for electrons having $E \approx 5 \times 10^9$ eV. Obviously, $T_e^{-1} = T_{e,e}^{-1} + T_{e,m}^{-1}$, where $T_{e,e}$ is the lifetime of electrons in the Galaxy against escape from the system (as a first approximation, $T_{e,e} = T$, the lifetime of the proton-nuclear component).

(*b*) *Volume and time-scale*

Unfortunately, the most important and, yet, least clear point of the model discussed is the choice of a large volume for the region 'filled' by cosmic rays. As a matter of fact, in assuming a model with an *extended halo*, we consider the magnetic fields in the halo to be quasi-closed or sufficiently chaotic. The latter may be seen from the fact that the time-scale for particle outflow is sufficiently long: $T \approx 3 \times 10^8$ years, see above under (*a*)(*ii*). It is unlikely that T may be decreased by more than one order of magnitude. This is indicated, for example, by the abundance of ^{10}Be, which allows the estimate $T > 5 \times 10^7$ years, see Section 2*b* (*vi*). If we ignore this result as being preliminary (Daniel and Durgaprasad 1966), and proceed from other considerations, we nevertheless obtain $T > 3 \times 10^7$ years for the model under discussion, with the large volume occupied by cosmic rays. Indeed, with $x = 3$ g/cm^2 for the thickness of matter penetrated and with $T \approx 3 \times 10^7$ years, the mean gas density becomes $\rho = x/cT \approx 10^{-25}$ g/cm^3, and the total mass of gas $M = \rho V \approx 10^{43}$ to 10^{44} g. However, the mass of gas in the disk is equal to some 3×10^{42} g, and for a number of reasons it is not believed possible to have much more gas in the halo. Finally, any decrease of the time T gives rise to an increase of the, already very strict, requirements for the power of the sources (see equation (9)).

The alternative galactic model misses a pronounced halo; it assumes a *disk* shape for the region occupied by cosmic rays. Since (cf. Baldwin, Paper 56, Section 1) the radio disk has a radius $R \approx 3 \times 10^{22}$ cm, and a thickness $h \approx 700$ pc $\approx 2 \times 10^{21}$ cm, the volume of the system is in this case $V_d \approx 10^{67}$ cm^3, while the energy of cosmic rays $W = w_G V_d \approx 10^{55}$ erg. However, the time of escape, T, in such a system will probably be very small. In fact, to leave the system the particles must travel the path $h/2$, hence $T \approx h^2/8D \approx 5 \times 10^{41}/D$. At $D \approx 10^{29}$ cm^2/sec, the time $T \approx 5 \times 10^{12}$ sec $\approx 10^5$ years! Even if one takes $T \approx 3 \times 10^5$ years, the power of sources in the disk model is $U = W/T = 10^{42}$ erg/sec, i.e. two orders of magnitude more than in the halo model (see equation (9)). Besides, there are nearly insurmountable difficulties in this model with the chemical composition and the isotropy of cosmic rays. With $T \approx 3 \times 10^5$ years and the thickness $x \approx 3$ g/cm^2, the mean gas density in the model is $\rho = x/cT \approx 10^{-23}$ g/cm^3, which is not permissible: the gas mass in the disk would become $M = \rho V_d \approx 10^{44}$ g. Because of the large gradient of cosmic-ray concentration, we should also expect a very large degree of anisotropy.

In short, one cannot have a galactic model of cosmic-ray origin without a halo*. The inverse conclusion is also true, provided the density of cosmic rays within the Galaxy is significantly higher than that outside; in this case formation of a halo is to be expected. On the one hand it follows from simple dynamical considerations: under the influence of the pressure of cosmic rays, a 'bubble' must be formed, containing gas and magnetic fields; this bubble may be considered as a halo. On the other hand, the tendency to formation of a halo is clearly understood from the analysis of the movement of cosmic rays in the galactic magnetic field, which falls off gradually into intergalactic space (Parker 1965).

As far as we know there are no real arguments against the assumption of a sufficiently extended halo around the Galaxy. As a matter of fact, the doubts expressed on this score are only of a quantitative character. Thus, the effective radius of the halo is supposed by some to be closer to 10 kpc than to 15 kpc. Also, the strength of the field in the halo may be closer to 2 than to 5 μG (=micro-gauss); this is connected with the fact that the radio luminosity of the halo is found to be less than was thought before. It is quite evident that the galactic model with a halo as described above is based on a rough estimate of the radius of the region filled by cosmic rays: the values $R = 3 \times 10^{22}$ and $R = 5 \times 10^{22}$ cm are quite equivalent from that point of view; the only important point is that $R \gg h \approx 2 \times 10^{21}$ cm—see also Paper 61 (Ginzburg).

(c) *Intensity variations*

Having adopted the galactic model including a halo, we turn to two other basic problems. The first deals with the changes of the intensity of cosmic rays in time. As pointed out above (Section 4*a*), we find it most reasonable to assume that the system *as a whole* is quasi-stationary; strong variations of intensity are surely possible for small regions near supernovae shells, etc. The alternative hypothesis is that the main part of cosmic rays observed now was formed by a powerful explosion in the galactic nucleus.

As far as we know, even the hypothesis of *small explosions in the nucleus* of the Galaxy, although probable, cannot be considered as proved. 'Small' explosions in the nucleus, transferring $W_{\mathrm{nucl}} \lesssim 10^{55}$ erg of energy to the cosmic rays, would increase the cosmic-ray intensity near the Earth by not more than 10% (if the total energy of cosmic rays in the Galaxy is $W \approx 10^{56}$ erg). Such an increase, having taken place as long as 3×10^7 to 3×10^8 years ago, can hardly be established and would leave the quasi-stationary picture unaffected. In addition, with explosions recurring on the average every 3×10^7 years, the power injected is $U_{\mathrm{nucl}} = W_{\mathrm{nucl}}/T_{\mathrm{nucl}} \approx 10^{40}$ erg/sec. In other words, small explosions in the nucleus could serve as sufficiently effective sources of cosmic rays in the Galaxy.

We do not see any grounds for the hypothesis of a *'big' explosion in the galactic nucleus*, having occurred some 30 to 100 million years ago, and having transferred $W_{\mathrm{nucl}} \gtrsim 10^{56}$ to 10^{57} erg of energy to the cosmic rays. As a matter of fact, this hypothesis would imply that the Galaxy just recently was a radiogalaxy but, nevertheless, has preserved its structure and apparently almost 'forgotten' about the catastrophe. We shall not linger here with the other objections set forth by us elsewhere (Ginzburg and Syrovatskij 1964, p. 209), but we underline that there is no observational confirmation whatever

* We recall that Pikel'ner (1953) founded his hypothesis about the existence of a halo around the Galaxy on considerations connected with the storage of cosmic rays.

for a non-stationary galactic model of the origin of cosmic rays, in which a major part or even all of the cosmic rays now observed would have originated in a 'big' explosion. The data about meteorites do not indicate strong variations in the intensity of cosmic rays during the last 10^9 years. The abundance ratio L/M for the nuclei in the L- and M-groups appears to increase toward the non-relativistic energy region (see Section 2*b* (*vii*)), while in a non-stationary model the ratio L/M should decrease with energy. The existence of cosmic-ray electrons with energies $E > 10$ GeV also indicates that these particles could not be accelerated during a period removed from our epoch by more than 3×10^7 years. The assumption that a big explosion of the galactic nucleus occurred less than 3×10^7 years ago is particularly improbable.

Thus, we have put forward arguments in favour of the *quasi-stationary galactic model* including a halo. We shall now discuss the problem of the sources of cosmic rays in this model.

(*d*) *Sources of cosmic rays*

(*i*) *The Sun* supplies an average of 10^{24} erg/sec to the cosmic rays; the chemical composition and the energy spectrum of solar cosmic rays differ from those of galactic cosmic rays. However, even if one leaves spectrum and composition out of consideration, the inefficiency of quiet stars is obvious from the point of view of the energy supply. Thus, 10^{11} *stars of solar type* would deliver only 10^{35} erg/sec to the cosmic rays, which is five orders less than the required value (equation (9)).

(*ii*) As is well known, *supernova explosions* are able to supply the required power. In fact, if during the explosion on the average an energy $W_{sn} \approx 10^{50}$ erg is transmitted to the cosmic rays, and explosions occur only once every 300 years,* then the power injected is already $U_{sn} = W_{sn}/T_{sn} \approx 10^{40}$ erg/sec. The data concerning the supernovae of 1054, 1572 and 1604 and about Cassiopea A indicate the plausibility that, as a result of the explosion and during the subsequent time interval, the relativistic electrons were accelerated with a total energy of 10^{48} to 10^{49} erg per supernova. This is sufficient for maintaining an equilibrium with respect to the electron component (see equation (10)). If one assumes that the energy of all cosmic rays in the supernova shells is two orders of magnitude greater than the energy of relativistic electrons, then the required power injection will be ensured for all the cosmic rays in the Galaxy. The additional hypothesis introduced here is completely natural. Both the example of the Sun and theoretical considerations point to the fact that the acceleration of the proton-nuclear component may definitely be more effective than the acceleration of electrons, which experience additional losses. From the energy point of view, too, the acceleration of cosmic rays to a total energy of 10^{49} to 10^{51} erg is possible during a supernova explosion.

(*iii*) Besides supernovae, *small explosions in the galactic nucleus* may be effective sources of cosmic rays (see Section 4*c*).

(*iv*) A certain contribution, especially at lower energies, may come from *novae* (Ginzburg and Syrovatskij 1964, p. 200) and from *X-ray sources* such as Sco X–1. According to the latest data (Gursky *et al.* 1966), the source Sco X–1 is star-like and may represent an object of a new type, a collapsing magnetic star (Ginzburg 1964, 1965*a*, Manley 1966). The X-ray emission in this case is of synchrotron character, and the acceleration of particles (not only electrons but also protons and nuclei) must be very effective: it is still difficult to estimate the power of such injectors, but if the full X-ray

* The best estimate is once every 50 years.

luminosity of these objects is approximately 10^{38} erg/sec (which appears quite realistic), an energy transfer to the cosmic rays of 10^{39} to 10^{40} erg/sec is not improbable*.

To conclude, we do not see any obstacles in the way of an adequate cosmic-ray power supply on the galactic model. However, the *possibility* of injection does not prove that this injection actually occurs. In this connection the galactic model cannot be regarded as proved. We only claim to have shown that this model is realistic and probable. In such a situation the analysis of alternative models, and especially the metagalactic models, is most important for us. If one succeeded in proving reliably that these models are unfounded, this would be evidence of the validity of the galactic model for the origin of cosmic rays.

5. METAGALACTIC THEORIES OF THE ORIGIN OF COSMIC RAYS

The metagalactic models assume that the main part of cosmic rays observed near the Earth are generated outside the Galaxy. Certain variants of this theory are indicated in Figure 1.

(a) *Three types of metagalactic model*

(*i*) In one of these the energy density of cosmic rays *anywhere* in metagalactic space is of the same order as in the Galaxy, i.e.,

$$w_{\mathrm{Mg}} \approx w_{\mathrm{G}} \approx 10^{-12}\ \mathrm{erg/cm^3}. \tag{11}$$

(*ii*) In another model the relation (11) refers only to the *vicinity of the Galaxy*, for instance to the Local Group of galaxies or to the Local Supergalaxy (the existence of this supergalaxy is not yet proved, but is believed possible). Such a local metagalactic model is most probably non-stationary, and in this respect is related to the non-stationary galactic model. The significant difference is, however, that the local metagalactic model considers a nearby radiogalaxy, for example Centaurus A (distance 3·8 Mpc $\approx 10^{25}$ cm), as the source of cosmic rays in the Galaxy.

If the cosmic rays in intergalactic space are *isotropic*, the condition (11) is practically inevitable within the framework of metagalactic models, at least in the neighbourhood of the Galaxy. Indeed, in the stationary case Liouville's theorem says that the intensity of cosmic rays is constant along the particle trajectories. If the cosmic rays are isotropic in the Metagalaxy as well as in the Galaxy, it follows that the energy density of metagalactic cosmic rays in the Galaxy is $w_{\mathrm{Mg,G}} = w_{\mathrm{G}}$. The same conclusion can be derived from more detailed consideration of the motions of particles passing from the Metagalaxy (magnetic field H_{Mg}) to a region with the galactic magnetic field $H_{\mathrm{G}} \gg H_{\mathrm{Mg}}$.

(*iii*) Allowance for non-stationary conditions, in which Liouville's theorem does not apply, makes it possible in principle to avoid the equality $w_{\mathrm{Mg,G}} = w_{\mathrm{G}}$. However, in the concrete cases of our Galaxy and of other galaxies, we do not see any conceivable mechanism which could 'pump' cosmic rays from metagalactic space into the Galaxy**. Therefore, if condition (11) is not fulfilled everywhere in metagalactic space, the only

* At the Symposium, Rossi (Paper 75) has reported that the X-ray source Sco X−1 is most probably an old nova. In this case there are, of course, no grounds to consider X-ray stars as a *special* type of cosmic-ray source.

** At the Symposium Puppi, Setti and Woltjer (Paper 47) have pointed out the possibility that cosmic rays in the Galaxy are pumped by neutral-hydrogen clouds falling down from the Metagalaxy. Even if this mechanism works at all, it is unlikely that the resultant compression of cosmic rays in the Galaxy will be large and permanent.

possibility of obtaining the high value of $w_{Mg,G} \approx w_G \approx 10^{-12}$ erg/cm^3 depends on the assumption of a strong *anisotropy* of cosmic rays in metagalactic space. In this connection one may discuss a third metagalactic model (see Figure 1), in which the cosmic rays in metagalactic space are strongly anisotropic and $w_{Mg} \ll w_G$. In such a model the cosmic rays, being isotropic in the region of the galactic magnetic field H_G, escape into intergalactic space, where the field $H_{Mg} \ll H_G$, with conservation of the adiabatic invariant $H^{-1} \sin^2 \theta =$ const. Thus, in the Metagalaxy there must be a strong anisotropy: $\theta_{max} = (H_{Mg}/H_G)^{1/2}$, and $w_{Mg}/w_G = H_{Mg}/(2H_G)$. At $H_{Mg} \approx 3 \times 10^{-9}$ gauss, $H_G \approx 3 \times 10^{-6}$ gauss, and $w_G \approx 10^{-12}$ erg/cm^3, we have $\theta_{max} \approx 1°$ and $w_{Mg} \approx 10^{-15}$ erg/cm^3.

The problem of the anisotropy of cosmic rays turns out, therefore, to be important and requires detailed discussion. Ginzburg (1965*b*; see also Ginzburg and Syrovatskij 1966*a*, 1966*b*) concluded that anisotropy was impossible. (We do not speak about situations of non-uniform space distribution, where anisotropy is simply related to the existence of a diffusion flow.) If one agrees with this conclusion, the only real possibility to preserve the metagalactic theory of cosmic-ray origin consists of allowing for (11) or at least assuming $w_{Mg} \approx w_G$. This very assumption is the basis of metagalactic models; the latest papers along this line are Burbidge and Burbidge (1966) and Gould and Ramsay (1966). Meanwhile, there are a number of reasons to doubt the validity of relation (11) and, rather, to consider the following condition to be fulfilled:

$$w_{Mg} \ll w_G \approx 10^{-12} \text{ erg/cm}^3. \tag{12}$$

To be specific, we believe it more probable that $w_{Mg} \lesssim 10^{-15}$ erg/cm^3. We shall briefly mention the arguments in favour of the inequality (12).

(*b*) *Comparison of metagalactic and galactic cosmic-ray energy densities*

(*i*) The kinetic-energy density of the metagalactic gas is $K_{Mg} = \frac{1}{2}\rho u^2 \leqslant 10^{-14}$ to 10^{-15} erg/cm^3, since $\rho \lesssim 10^{-29}$ g/cm^3, $u = (1 \text{ to } 5) \times 10^7$ cm/sec. Since $H_{Mg} < 10^{-7}$ gauss, the energy density of the metagalactic magnetic field is $H_{Mg}^2/8\pi \lesssim 10^{-15}$ erg/cm^3; it probably even is less than 10^{-16} to 10^{-17} erg/cm^3. It would be difficult and unnatural to presume that the cosmic-ray energy density, w_{Mg}, appreciably exceeds the densities K_{Mg} and $H_{Mg}^2/8\pi$. Hence, we estimate $w_{Mg} \lesssim 10^{-15}$ erg/cm$^3 \ll w_G$.

(*ii*) An estimate of the density of cosmic rays penetrating into metagalactic space *from normal and radiogalaxies* leads to the value $w_{Mg} \approx 10^{-16}$ to 10^{-17} erg/cm^3; in any case we do not see any possibility to obtain values of w_{Mg} comparable with w_G. To elucidate this statement we stress that powerful radiogalaxies and quasars are rather rare: the nearest quasar, 3C 273B, is at a distance of 500 Mpc, and the powerful radiogalaxy Cyg A is at about 200 Mpc distance. Suppose, for example, that in a sphere of radius 100 Mpc, that is in a volume $V \approx 10^{80}$ cm^3, there is always present a source of the Cyg A type, which delivers 10^{61} erg of cosmic-ray energy per explosion. Over a period of 10^{10} years, 10^4 explosions are expected with a duration of the order of 10^6 years each. Thus, some 10^{65} erg are injected in the given volume and, even without allowance for the adiabatic decrease of energy due to the expansion of the Metagalaxy, the mean density of cosmic rays would become $w_{Mg} \approx 10^{65}/10^{80} = 10^{-15}$ erg/cm^3 $\approx 10^{-3}\, w_G$. In fact the value w_{Mg} will be even smaller*.

* The estimate given by M. Schmidt in the discussion (Paper 81) is quite consistent with this conclusion.

(*iii*) The absence of a notable radio-emission from intergalactic space allows certain conclusions concerning the intergalactic magnetic field, H_{Mg}, and the energy density, $w_{e,Mg}$, of the *electron component of metagalactic cosmic rays*. Thus, for $H_{Mg} \approx 3 \times 10^{-8}$ gauss we have $w_{e,Mg} \leqslant 10^{-2}\ w_{e,G} \lesssim 3 \times 10^{-16}$ erg/cm³, where $w_{e,G}$ is the energy density of the electron component in the Galaxy.

(*iv*) The established upper limit of the *flux of cosmic γ-rays* (see Ginzburg and Syrovatskij 1964 and below) allows us to estimate an upper value of $w_{e,Mg}$. Even assuming that the energy density of optical emission in the Metagalaxy is $w_{ph} \approx 2 \times 10^{-3}$ eV/cm³, we obtain $w_{e,Mg} \lesssim (1 \text{ to } 3) \times 10^{-2}\ w_{e,G}$. It is more probable that $w_{ph} \approx 10^{-2}$ eV/cm³ and thus $w_{e,Mg} < 10^{-2}\ w_{e,G}$. Hence, for w_{Mg} we reach the same conclusion as under (*iii*). An even lower value for $w_{e,Mg}$ follows from consideration of the metagalactic thermal emission of 3 °K brightness temperature and energy density $w_{ph} \approx 0{\cdot}4$ eV/cm³. In such a radiation field, the electrons of energy 10^{10} eV lose as much as half their energy by Compton losses in $T_C \approx 10^8$ years. The scattering of radiophotons of mean energy $\epsilon_T = 2{\cdot}7\ kT = 7 \times 10^{-4}$ eV by relativistic electrons will give rise to the appearance of background X-ray emission. Using the data about the isotropic X-ray background, we estimate $w_{e,Mg} \lesssim 3 \times 10^{-5}$ eV/cm³ $\lesssim 10^{-3}\ w_{e,G}$.

Here, as well as above, the electrons and the emission are assumed to fill the whole Metagalaxy. But $w_{e,Mg} \lesssim 0{\cdot}1\ w_{e,G}$ even if the electron component is localized in a region some 15 Mpc = 5×10^{25} cm $\approx 10^{-2}\ R_{ph}$ in size, where $R_{ph} \approx 5 \times 10^{27}$ cm is the photometric radius of the Metagalaxy. Thus, for the Metagalaxy as a whole, or even for a region near the Galaxy with a radius exceeding 10 Mpc,

$$w_{e,Mg} \ll w_{e,G}; \tag{13}$$

analogous conclusions have been reached by Fazio *et al.* (1966) and by Felten and Morrison (1966). This implies that, for metagalactic models other than a purely local one, the electron component of cosmic rays must be regarded as originating in the Galaxy. This makes the metagalactic model as a whole even less probable (see below).

(*v*) From data concerning the *cosmic background X-ray emission*, together with certain additional assumptions (Ginzburg and Syrovatskij 1966*a*, 1966*b*; Ginzburg and Ozernoj 1965) one can conclude that $w_{Mg} \lesssim 10^{-15}$ erg/cm³. If w_{Mg} exceeded 10^{-15} erg/cm³, we should expect too much heating of the metagalactic gas.

(*vi*) A value of 10^{-17} to 10^{-15} erg/cm³ for w_{Mg} is really not small, even if one compares the energy of metagalactic cosmic rays not only with the energy densities K_{Mg} and $H_{Mg}^2/8\pi$ in intergalactic space (see (*i*) above), but also with the kinetic energy of the *random motions of galaxies*.

(*vii*) There are no data violating the inequality (12); at the same time there are no arguments in favour of the assumption that $w_{Mg} \approx w_G$, except the possibility that the cosmic rays in the Galaxy (but not those in radiogalaxies and in quasars!) have a metagalactic origin. Meanwhile a metagalactic theory of this kind encounters extra difficulties regarding the chemical composition of cosmic rays: metagalactic cosmic rays formed during the pregalactic stage of evolution of the Metagalaxy would probably be poor in heavy elements; as shown above, cosmic rays which originated in galaxies and quasars are in all probability insufficient to accumulate an energy density w_{Mg} of the order of w_G.

(c) *Conclusion*

To summarize we conclude that in the framework of metagalactic models one must inevitably restrict oneself to consideration of the proton-nuclear component; the electron component must be considered as galactic (Figure 1). But this eclectical scheme is particularly improbable, as was already stressed. Indeed, from Section 4 it is clear that the galactic theory for the origin of the *electron component* of cosmic rays is connected with assumptions about the existence of a halo, and about a sufficiently powerful injection of electrons as, for instance, during supernova explosions. The only significant additional step in passing from such a scheme to a theory for the galactic origin of *all cosmic rays* consists in the assumption that the injection of protons and of nuclei occurs with an efficiency one or two orders of magnitude greater than that of electrons. It is known that in the Sun the generation of the proton-nuclear component is indeed more effective than that of the electron component. This fact appears quite natural, particularly because the synchrotron and Compton losses, which are considerable for electrons, are practically absent for protons and nuclei. Note also that the local metagalactic model would have to be non-stationary. Several considerations from Section 4 argue against this possibility.

We thus believe that everything testifies against the metagalactic models, though some of them cannot be regarded as completely disproved. From the foregoing discussion certain directions of investigation become clear which may promote the clarification of this question. For example, one of the (in principle) simple methods consists of measuring the anisotropy of cosmic rays. Within the framework of the galactic theory the cosmic rays must flow from the Galaxy (a radial change of the flux direction due to local magnetic fields is improbable). Preliminary anisotropy data lead to this very result. Furthermore, the cosmic rays (protons and nuclei) are believed to create π°-mesons in intergalactic space and consequently to produce γ-rays. The intensity of such γ-emission (Ginzburg and Syrovatskij 1964, p. 28) is

$$I_{\gamma} \approx \sigma n\, I_{\mathrm{Mg}}\, R_{\mathrm{ph}} \approx 3 \times 10^{-3}\, I_{\mathrm{Mg}} \text{ photons cm}^{-2}\,\text{sec}^{-1}\,\text{sr}^{-1}, \tag{14}$$

where $n \approx 10^{-5}$ cm^{-3} is the most probable gas density in intergalactic space, $R_{\mathrm{ph}} \approx 5 \times 10^{27}$ cm, and I_{Mg} is the intensity of metagalactic cosmic rays; in the Galaxy $I_{\mathrm{G}} \approx 0{\cdot}3$ particles cm^{-2} sec^{-1}, see Section 1. According to observation, $I_{\gamma} < 3 \times 10^{-4}$ photons cm^{-2} sec^{-1} sr^{-1} and, thus, $I_{\mathrm{Mg}} < 0{\cdot}3\, I_{\mathrm{G}}$. For the time being this result is not very informative, owing to the low accuracy of calculations and measurements. However, it is clear that in future one may hope to measure directly the mean intensity of the proton-nuclear component of cosmic rays in the Metagalaxy using the methods of γ-astronomy. We have already mentioned indirect methods of estimating the intensity, I_{Mg}, and the corresponding energy density, w_{Mg}; all these methods argue in favour of the inequality

$$w_{\mathrm{Mg}} \ll w_{\mathrm{G}} \approx 10^{-12}\ \text{erg/cm}^3.$$

6. CONCLUDING REMARKS

The competition between galactic and metagalactic theories of the origin of cosmic rays has continued for several years. The galactic theories have always seemed to us the most probable, and this belief is strengthened as time goes on. But the dilemma, as we have already seen, is not yet finally solved, and one cannot yet dispose of all metagalactic models. The causes of this situation are evident to the astronomers; to physicists,

unfortunately, they are more difficult to explain. The trouble is, first, with the incompleteness and uncertainty of our data about the galactic halo, as well as about the configuration of magnetic fields in the disk, the halo and the transition region to intergalactic space. Second, our knowledge of cosmology (the early stages of evolution, the formation of clusters and galaxies, the temperature and density of metagalactic gas) is quite insufficient, as are our data about explosions of supernovae and of galactic nuclei, and about the nature and formation mechanism of quasars. For these reasons it is so difficult to strictly disprove the metagalactic theories of origin of cosmic rays.

In this connection it is no accident that metagalactic models of cosmic-ray origin are often discussed together with other 'unorthodox' theories, such as the steady-state cosmology and the local theory of quasars. Evidently, if the steady-state cosmological model were true, i.e. if no evolutionary effects on a metagalactic scale occurred, certain metagalactic theories of cosmic-ray origin would be difficult to disprove. Why not consider, for instance, the new matter which appears in the steady-state theory as being directly formed as cosmic rays? Further, if the quasars are formations ejected from the Galaxy and from nearby radiogalaxies at a speed comparable with that of light, the local metagalactic model of cosmic-ray origin seems rather natural.

We must mention in this connection that we are now, and have been before, strongly opposed to the steady-state cosmology as well as to the local theory of quasars. We think (as perhaps do many others) that for making far-reaching hypotheses, such as the creation of new matter, or the ejection of giant masses of gas from galactic nuclei at relativistic velocities, one needs weighty grounds. Neither the lack of direct contradiction with observations, nor a general argument about the possibility of trespassing the limits of known physical laws is sufficient in this respect. Surely the decisive word is with the observations. All known data testify against steady-state cosmology and the local theory of quasars. As to cosmology we mention the evolutionary effect in radio-sources (the density of distant sources appears higher than that of nearby sources) and the thermal metagalactic emission of 3 °K brightness temperature. The absence of blue-shifts in spectral lines speaks against the local theory of quasars: on the local model of quasars, the number of objects having a blue-shift must even exceed that having a red-shift; in fact there are more than 50 quasars with red-shifts and not one with a blue-shift. The local theory further encounters big energy difficulties and, at any rate, is not confirmed by the observations of absorption in the spectra of quasars. Note also that one of the arguments in favour of the local theory is that the cosmological models of quasars encounter severe difficulties (Hoyle and Burbidge 1966). However, we do not agree with this point of view (Ginzburg and Ozernoj 1966, 1967); nor do we see that any obstacle to the assumption of cosmological distances would be comparable to the difficulties met in the local theory of quasars. It is true that there is no unanimity yet about these problems, and it is likely that we still need additional data before we can finally disprove the steady-state cosmology and the local theory of quasars. For the purpose of this report, it is important that these two theories are not confirmed and rather meet new objections. Therefore, the metagalactic theory of cosmic rays, which is our prime concern here, finds no additional confirmation from these theories.

The aim of these remarks is not to relax attempts to check the extravagant astronomical hypotheses in all possible ways. Actually, the very possibility to seriously discuss such hypotheses reflects the modern state of extragalactic astronomy. The absence of obvious solutions is characteristic for many of the most fundamental problems which look

'simple'. The problem of the radio-halo of the Galaxy and that of intergalactic matter may serve as examples. We have, evidently, attempted to stress two other quite different points: the existence and the discussion of extravagant hypotheses should not make the impression (which we sometimes experience) that 'everything is possible' in the realm of extragalactic astronomy; and the efforts not to dismiss the simplest models, unless there are strong reasons to do so, are a matter of taste and hardly of conservatism. In fact, nowadays, there is every reason to consider the galactic model for the origin of the main part of cosmic rays near the Earth as the most probable and, if desired, as the best 'working hypothesis'. At the same time, the existence of metagalactic models of the origin of cosmic rays may be regarded as a warning signal to make us glance back and to keep us from forgetting the possible obstacles in the way of further investigations.

REFERENCES

Agrawal, P. C., Damle, S. V., Gokhale, G. S., Joseph, G., Menon, M. G. K. 1966, in *Proceedings Ninth International Conference on Cosmic Rays* (London, September 1965), Ed. A. C. Stickland, Vol. 1, publ. by the Institute of Physics and the Physical Society, London, p. 453.

Burbidge, E. M., Burbidge, G. R. 1966, in *Proceedings Ninth International Conference on Cosmic Rays* (London, September 1965), Ed. A. C. Stickland, Vol. 1, publ, by the Institute of Physics and the Physical Society, London, p. 92.

Cameron, A. G. W. 1959, *Astrophys. J.*, **129**, 676.

Daniel, R. R., Durgaprasad, N. 1966, *Progress theor. Phys.*, Osaka, **35**, 36.

Fazio, G. G., Stecker, F. W., Wright, J. P. 1966, *Astrophys. J.*, **144**, 611.

Felten, J. E., Morrison, Ph. 1966, *Astrophys. J.*, **146**, 686.

Ginzburg, V. L. 1964, *Dokl. Akad. Nauk SSSR*, **156**, 43 (translation in 1964, *Soviet Phys. Dokl.*, **9**, 329).

Ginzburg, V. L. 1965*a*, in *Quasi-Stellar Sources and Gravitational Collapse*, Eds. I. Robinson, A. Schild and E. L. Schucking, Univ. of Chicago Press, Chicago, p. 283.

Ginzburg, V. L. 1965*b*, *Astr. Zu.*, **42**, 1129 (translation in: 1966, *Soviet Astr.*, **9**, 877).

Ginzburg, V. L., Ozernoj, L. M. 1965, *Astr. Zu.*, **42**, 943 (translation in: 1966, *Soviet Astr.*, **9**, 726).

Ginzburg, V. L., Ozernoj, L. M. 1966, *Astrophys. J.*, **144**, 599.

Ginzburg, V. L., Ozernoj, L. M. 1967, Coherent Mechanism of Radio Emission in Quasars and Residuals of Supernovae, in IAU Symposium, no. 29, in press.

Ginzburg, V. L., Syrovatskij, S. I. 1964, *The Origin of Cosmic Rays*, Pergamon Press, Oxford.

Ginzburg, V. L., Syrovatskij, S. I. 1966*a*, in *Proceedings Ninth International Conference on Cosmic Rays* (London, September 1965), Ed. A. C. Stickland, Vol. 1, publ. by the Institute of Physics and the Physical Society, London, p. 53.

Ginzburg, V. L., Syrovatskij, S. I. 1966*b*, *Usp. fiz. Nauk*, **88**, 485 (translation in 1967, *Soviet Phys. Usp.*, **9**, 223.

Gould, R. J., Ramsay, W. 1966, *Astrophys. J.*, **144**, 587.

Gursky, H., Giacconi, R., Gorenstein, P., Waters, J. R., Oda, M., Bradt, H., Garmire, G., Sreekantan, B. V. 1966, *Astrophys. J.*, **144**, 1249.

Hoyle, F., Burbidge, G. R. 1966, *Astrophys. J.*, **144**, 534.

Kuževskij, B. M., Syrovatskij, S. I. 1965, *Zu. eksp. teor. Fiz.*, **49**, 1950 (translation in 1966, *Soviet Phys. JETP*, **22**, 1331).

Manley, O. P. 1966, *Astrophys. J.*, **144**, 1253.

Parker, E. N. 1965, *Astrophys. J.*, **142**, 584.

Pikel'ner, S. B. 1953, *Dokl. Akad. Nauk SSSR*, **88**, 229.

Stickland, A. C. (Ed.) 1966, *Proceedings Ninth International Conference on Cosmic Rays* (London, September 1965), Vol. 1, publ. by the Institute of Physics and the Physical Society, London.

Suess, H. E., Urey, H. C. 1956, *Rev. mod. Phys.*, **28**, 53.

Webber, W. R. 1967, *Handbuch der Physik*, Vol. 46/2, Springer Verlag, Berlin/Göttingen/Heidelberg, 181.

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72. RADIO-FREQUENCY EMISSION FROM SUPERNOVA EJECTA

S. A. Colgate

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A new mechanism is proposed for non-thermal radio emission, which depends upon the scattering of photons within an unstable counter-streaming plasma. This mechanism may play a dominant role in several phenomena:

(*i*) the short-wave emission from quasi-stellar sources;

(*ii*) the emission from symmetric supernova nebulae in the early stages of the nebular expansion;

(*iii*) maintenance or modification of the 3 °K black-body background radiation of the Universe.

From multiple supernovae (10 per year) a detailed model for the quasi-stellar sources has been constructed, which predicts the large energy emitted in the millimetre-wave range, together with its fluctuations. Plasma oscillations of large amplitude are induced in the counter-streaming plasma corresponding to the high-energy (more than 10 MeV/nucleon) external supernova mass fraction penetrating a low-density (about 10^{-18} g/cm^3) gas cloud. Electrostatic bremsstrahlung (analogous to synchrotron emission) by the 1-to-10-MeV electrons in the electric fields of plasma oscillation ($E \approx 10$ e.s.u.) creates the source photons with frequencies ν of 10^7 to 10^9 Hz. These photons scatter from the plasma oscillations with a cross-section enhanced by the factor $n_e \lambda_D^3 \approx 10^{17}$, where n_e is the electron density and λ_D the Debye length (Drummond 1962). The mean free path for scattering with a wave-number change, Δk, of the order of the plasma frequency is small enough that the source photons double their energy before reabsorption. Therefore, the electrostatic-bremsstrahlung emission flux 'diffuses up' in momentum space before appreciable reabsorption takes place. A photon leaves the plasma, when its frequency is so large that the root-mean-square scattering angle within the thickness of the plasma is less than a radian. This condition, the constancy of the diffusion flux in k-space, and the independence upon k of the cross-section for scattering with wave-number change Δk, lead to a $\nu^{1/2}$ power spectrum extending up to 10^{13} Hz, approximately as observed for the source 3C 273B.

The coupling between photon scattering and plasma oscillation is so strong that the radio emission is determined by the kinetic energy available to drive the plasma instability. This energy (10^{52} to 10^{53} erg) is sufficient to give the observed emission.

We shall now discuss briefly the probable total energy of supernovae. Any explosion gives rise to a velocity distribution of matter. The distribution calculated by Colgate and White (1966) contained a total of 10^{53} erg and gave 5×10^{51} erg in the velocity range 15 000 to 20 000 km/sec. This energy agrees well with that calculated for Tycho's Supernova as reported by Minkowski (Paper 62). The fact that other mass fractions should

contain more or less energy is not surprising. Actually the observed light (4×10^{49} erg) can not be obtained from the hydrodynamics alone, despite the theoretically extremely large energy. Instead, one must assume radioactive energy to obtain agreement with observation. The phenomena observed emphasize particular mass fractions. Thus, light tends to come from the slower, denser mass fractions. Why radio emission should come from the mass fraction moving at velocities around 17 000 km/sec is not obvious, unless this is the mass fraction associated with compression of the magnetic field. It is hoped that the faster mass fractions can be observed in the future.

REFERENCES

Colgate, S. A., White, R. H. 1966, *Astrophys. J.*, **143**, 626.
Drummond, W. E. 1962, *Physics Fluids*, **5**, 1133.

Discussion

G. L. Verschuur: What polarization properties are expected of this form of radio emission?

S. A. Colgate answers: Only a small, but finite, polarization is expected due to the scattering of plasma waves by plasma waves (plasmon-plasmon scattering). This scattering tends to isotropize the wave distribution, and is the major source of damping apart from the photon-plasmon scattering (i.e., radio emission). The theory of plasmon-plasmon scattering is only now being developed, and uncertainties do not permit an accurate estimate of the polarization. The short-wave source in 3C 273 is not significantly polarized.

V. L. Ginzburg asks: What are the probable and maximum estimates, according to your model, for the cosmic-ray energy and for the energy in the electron-component of the cosmic rays, for an average supernova explosion?

Colgate answers: The most probable total supernova energy is 10^{53} erg, the binding energy of the resulting neutron star. The mass fraction accelerated to energies greater than 1 GeV per nucleon (cosmic rays) is 10^{-4} of the ejected mass. For an ejection of $\frac{1}{2} M_{\odot}$, this corresponds to conversion into cosmic rays of 10^{50} erg per supernova. At the moment of ejection the fraction of this energy in the electron component is 1/2000, but as this matter interacts with the magnetic field, the electrons and ions tend to share energy. This is due to the well-known phenomena of charge separation at a diamagnetic surface. It would not be surprising if as much as 10% of the ion energy were converted to electron energy in this fashion.

F. D. Kahn: Your theory of the energization of photons by scattering requires the instability of space-charge waves in counter-streaming plasmas. But it has often been shown that such waves are quickly stabilized by the resulting widening of the electron velocity distribution. How does this affect your process?

Colgate answers: The widening of the electron velocity distribution is limited by the velocity of light. This is equivalent to a reduction of the effective mass ratio from 1 : 2000 to a ratio closer to unity, due to the rapid increase with velocity of the longitudinal mass of a relativistic particle. This mass increases as $\gamma^3 m_0$, where $\gamma \equiv (1 - \beta^2)^{-1/2}$. In the case of supernova excitation, the mass fraction exciting the instability has an energy of 100 MeV/nucleon, and so only a modest electron energy, $\gamma_e \approx 5$, already ensures sufficient longitudinal mass so that the instability will not be stabilized. Instabilities in two-stream computer models have been demonstrated for a mass ratio of 1 : 100.

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73. ON THE NATURE OF THE GALACTIC HALO

(Invited Discussion Contribution)

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The physical arguments for the existence of a galactic halo, as reviewed by Ginzburg in Paper 61 and by Ginzburg and Syrovatskij in Paper 71, have changed little in recent years. The observational evidence, according to the reports at this Symposium (Baldwin, Paper 56, Section 4; Burke, Paper 59; Mills, Paper 60; Discussion, Paper 63), has become more ambiguous than it appeared to be in the years following Baldwin's first work. While some observers still find indications for a halo not too different from the one originally proposed, others see little evidence in their data for its existence. In this situation it is natural to turn to other galaxies of similar type, of which some dozens have been observed with the necessary resolution. Of these, only M 31 shows enhanced emission (possibly of spotty character) out to distances comparable with its radius, while in a number of other galaxies no evidence for such emissions has been found so far.

The phenomenon of enhanced emission around some, probably small, fraction of galaxies of types Sb and Sc suggests that it may be typical for such galaxies, but a transient phenomenon, as was first suggested, I believe, by Burbidge and Hoyle (1963). In order to meet the theoretical requirements it should be quasi-stationary over a time scale of a hundred million years or so. Furthermore it should be kept in mind, as emphasized already by Ginzburg (Paper 61), that the halo demanded by the theory of cosmic rays is not necessarily a phenomenon conspicuous at radio frequencies.

These considerations do not of course answer the question what the situation in our Galaxy is. Two lines of evidence among those discussed here seemed to me relevant in this connection: first, the improved value of the magnetic field in the halo region, derived from the continuum radio observations and discussed by Van de Hulst in Paper 64; and second, the measurements of cosmic rays giving information on the radioactive decay of ^{10}Be, mentioned by Ginzburg and Syrovatskij (Paper 71, Section 2 (*b*) *vi*). The latter ones, if confirmed, would indicate a minimum value of the confining volume much larger than that of the disk.

In addition we have the important work, largely of the Dutch astronomers (Blaauw *et al.*, Paper 45; Oort, Paper 46), on the high-velocity clouds in intermediate and high galactic latitudes. These clouds should be in the halo region, though it is difficult to say at what distances. According to the most plausible interpretation of the still incomplete data, they have been slowed down considerably by their interaction with the halo; a full analysis will however not be available before some time.

To sum up: it seems more probable than not that our Galaxy has some kind of a halo as demanded by the physical theory, but no more precise statement appears justified at this stage.

REFERENCE

Burbidge, G. R., Hoyle, F. 1963, *Astrophys. J.*, **138**, 57.

74. DISCUSSION ON COSMIC RAYS AND RELATED PROBLEMS

I. COSMIC RAYS

J. R. Shakeshaft: In his Introductory Report (Paper 64), Van de Hulst showed the energy spectrum of cosmic-ray electrons compiled by Tanaka – see Figure 1. He attributed the change of slope at energies of about 1 GeV to solar modulation. Why should not this change of slope correspond to the change in differential spectral index of the radio emission at about 200 MHz, discussed by Baldwin (Paper 56, Section 5*b* and Figure 5)? The values of spectral index found by Tanaka above and below 1 GeV would fit quite well with the radio spectral indices above and below 200 MHz.

Y. Tanaka answers: We are inclined to attribute the bend ('knee') around 1 GeV to solar modulation, for two reasons: (*a*) the position of the knee coincides with the onset of solar modulation as deduced from the nuclear component of cosmic rays; (*b*) the electron spectrum above a few GeV is nearly parallel to that of protons and heavier nuclei.

If the observed knee is supposed to be caused by synchrotron and inverse-Compton losses, the production spectrum of electrons should have been one power flatter than that of the nuclear component. This seems to be difficult in all acceleration mechanisms proposed thus far.

On our picture, the energy spectrum of electrons above 2 GeV is interstellar.

J. Lequeux: Recently observations of the energy spectrum of primary electrons have been made by the Milano-Saclay groups. They have found $n(E)\,\mathrm{d}E \propto E^{-3.0 \pm 0.5}\,\mathrm{d}E$ for $E > 4.5$ GeV. One would then expect the high-frequency part of the galactic radio continuum to have a spectral index of -1.0 ± 0.25; as it is likely that this part is affected by synchrotron losses, the low-frequency part not affected by these losses would, in a stationary model of the Galaxy, have a spectral index of -0.5 ± 0.25, which is consistent with observations.

T. K. Menon asks Ginzburg: What is your interpretation of the difference in spectral index between the electrons and the heavier nuclei in cosmic rays?

V. L. Ginzburg answers: There is no doubt that theory must explain differences between the spectra of electrons and of protons and nuclei. We think that the electrons are not secondary, that is, they do not originate as a result of $\pi^\pm \rightarrow \mu^\pm \rightarrow e^\pm$ decay. Consequently, we should not expect a one-to-one correspondence between electron and proton spectra. At present, no precise theory of spectra exists at all. At this moment, I should like to mention only that a considerable fraction of the particles and in particular of the electrons could possibly leave the supernova envelopes at a very early stage of the explosion. Accordingly, there are no grounds for a numerical relationship between the spectra of electrons observed in the envelopes, and those of electrons injected into interstellar space as a result of supernova outbursts. An analysis of all these problems is undoubtedly one of the most urgent tasks for theory.

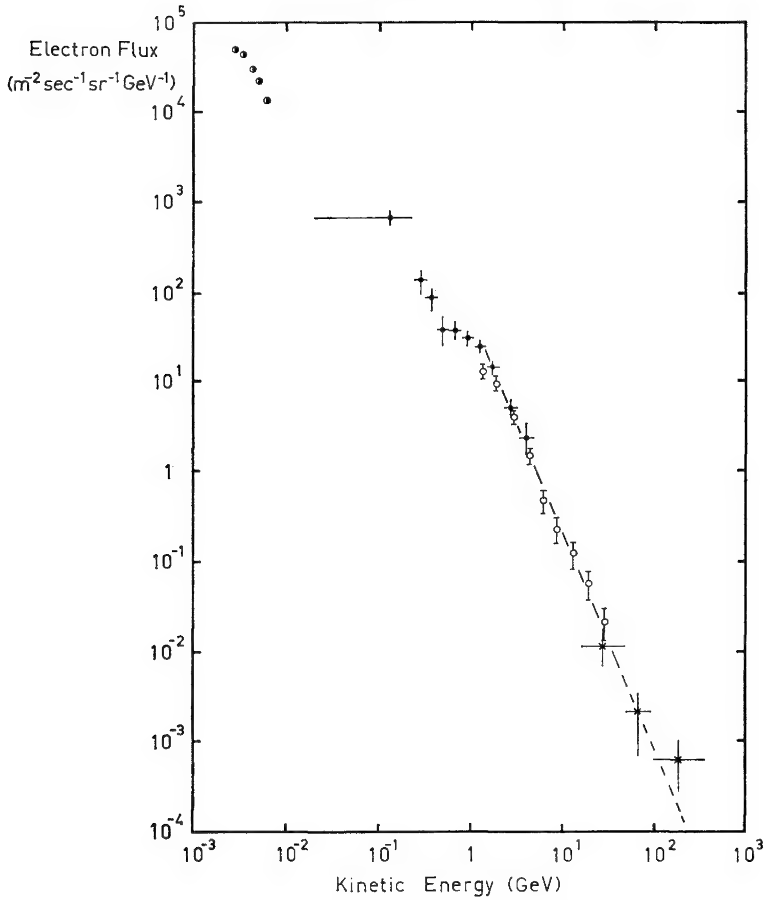

FIG. 1. Energy spectrum of cosmic-ray electrons. This is a composite diagram, prepared by Y. Tanaka from observations by Cline *et al.* (1964, half-filled circles), Meyer *et al.* (unpublished, dots), Bleeker *et al.* (unpublished, open circles), and Daniel and Stephens (1966, crosses). The exponent of the power law indicated by a dashed line is $\gamma = 2{\cdot}4$.

Tanaka: The electron spectrum shown in Figure 1 may serve for an estimate of the life-time of cosmic rays. If one admits that the knee caused by the growing importance of synchrotron and inverse-Compton losses does not appear below 20 GeV, the confinement time of cosmic rays in the Galaxy cannot be much longer than 10^7 years. From a combination with the thickness of matter traversed by cosmic rays, $x = 3\ \mathrm{g\ cm^{-2}}$ (see Ginzburg and Syrovatskij, Paper 71, Section 2 *b* (*i*)), it follows that the cosmic rays are predominantly distributed in the disk, so that the halo would be 'cosmic-ray thin'.

Lequeux: Recent balloon observations by the Milano-Saclay groups have shown that the ratio $e^+/(e^+ + e^-)$ is less than 10% for energies higher than 4·5 GeV. This figure is considerably more certain than those derived previously, because of the large number of events observed.

I. S. Šklovskij: I should like to stress that radio astronomy gives information only on the distribution and on the spectrum of relativistic electrons. When Ginzburg and Syrovatskij proved that such electrons cannot be secondary, the connection between 'true' cosmic rays (protons and nuclei) and relativistic electrons was lost. Moreover, it is possible to show that some sources, for instance the Crab Nebula, inject mainly relativistic electrons into the interstellar medium, and few protons. Another example is the Magellanic Clouds; there we have no nucleus, three observed supernovae being the only source of cosmic-ray electrons. This point of view may be checked by energy considerations based on the observed radio properties.

G. R. Burbidge: Ginzburg has given an excellent review (Paper 71) of the possible places of origin of the cosmic rays. He concludes that the weight of the evidence suggests that the cosmic rays are produced by supernovae or other violent events in our Galaxy. I should like to emphasize that there are a number of arguments which suggest to me that the bulk of the cosmic rays may have an extragalactic origin. We are agreed that the situation concerning the observational evidence for a galactic halo of radio emission is confused, and the sense of the argument (cf. Ginzburg, Paper 61) here has been that, even if one cannot detect a halo, there are good theoretical reasons to believe that extended distributions of low-density gas and magnetic field may be present outside the immediate vicinity of the galactic plane. However, this does not answer the important question concerning the trapping properties of such a distribution, and we know that, unless the cosmic rays of galactic origin can be trapped efficiently, the galactic theory is in difficulty. I see no reason to believe that the halo, even if it exists, will be an effective trap.

As far as the supernovae as sources are concerned, it is still not possible to show from observation that enough particles can be injected into interstellar space from supernova explosions. One has to rely on theory, perhaps that developed by Colgate. But such arguments can also be used to demonstrate that very large energies arise in explosions in extragalactic sources.

Finally, as indicated by me several years ago, the frequency of radio sources is such that particles injected by them may be able to account for a significant fraction of the cosmic rays.*

Ginzburg answers: According to our estimates, the contribution of radio-galaxy explosions, quasars and normal galaxies to the cosmic-ray energy density in metagalactic space, w_{Mg}, cannot exceed 10^{-15} to 10^{-16} erg cm^{-3}. In this estimate it is assumed that the total energy of cosmic rays in the source is of the same order of magnitude as the magnetic energy in the source. This assumption corresponds to the minimum of required energy, and has other grounds as well. Radio galaxies and quasars can contribute $w_{Mg} \gg 10^{-15}$ erg cm^{-3}, to be precise: $w_{Mg} \approx 10^{-12}$ erg cm^{-3}, only if we assume (as Burbidge presently does) that the energy of cosmic rays in the sources is many orders of magnitude greater than the magnetic energy. The cosmic-ray energy in the sources then reaches extraordinarily high values: something like 10^{64} to 10^{66} erg for powerful radio galaxies like Cyg A.

I do not see any reason for such a hypothesis. At the same time, of course, I admit that the value of w_{Mg} is uncertain. It will be possible to answer this question by

* Cf. the discussion by Schmidt and Burbidge in Paper 81.—*Editor.*

measurement, in particular if one succeeds in measuring with better accuracy the intensity of gamma-rays arising from π° decay in metagalactic space (see Paper 71, Section 5*c*).

H. Alfvén: Ginzburg has said (Paper 71, Section 1) that it is absolutely clear that cosmic radiation plays a decisive role in the Galaxy. I am not at all sure about this, because what we observe and what we conclude from observation are so different. If we assume a magnetic field of 10^{-5} gauss, the radius of curvature for particles with energies of 10^{15} eV is less than 10^{17} cm, that is, one-tenth of a light-year. Yet we assume that they fill a very large region and indeed penetrate a considerable part of our Galaxy. I cannot see any reason for this, because no theory exists about the problem of cosmic rays in our neighbourhood; and no theory *can* exist, because it must depend on local magnetic fields, in a region less than a light-year in size, and very little is known about these local fields. It may very well be that 99% of the cosmic radiation is a local phenomenon confined to our environment in the same way as the Van Allen radiation belts are confined to the Earth's magnetic field. The high-energy particles, of course, would move around in larger regions.

Ginzburg answers: The arguments against the solar or local origin of cosmic rays are numerous. In our book, we have analyzed the question in a special subsection (Ginzburg and Syrovatskij 1964, p. 215). I shall mention only in passing the difficulties in explaining the chemical composition and the energy spectrum of the observed cosmic rays on the basis of a solar origin. The radio-astronomical evidence, however, is quite strong. According to this, relativistic electrons are present in a gigantic region outside the solar system; although the halo is open to discussion, there is no question about the presence of cosmic-ray electrons in the disk, in densities comparable to those near the Earth. This fact by itself, according to my view, suffices to show that it is impossible to limit the region filled by cosmic rays to the direct neighbourhood of the Sun. However, I agree that it is extraordinarily difficult to disprove anything.

Alfvén: To disprove anything is very difficult, but also to prove it.

Ginzburg: Fortunately it is possible to do something. I have worked in the field for some years, and I can say in the course of time the argument slowly improves. So I hope during my lifetime I shall see the full victory of these things.

Alfvén: I hope you will live very long.

We do not know the interstellar chemical composition within a light-year around the Sun, as far as I know, at least not well enough to really win the argument concerning the chemical composition. The similarity between the density of cosmic rays in our neighbourhood and that of relativistic electrons in the Galaxy is of course an extremely indirect argument. Therefore I still cannot see any reason for supposing that the cosmic-ray density anywhere in the whole Galaxy is the same as or within, say, one power of ten less than we measure in our environment.

I would prefer to speak about local origin, rather than solar origin.

2. THE GALACTIC HALO

J. R. Shakeshaft: With regard to haloes of other galaxies, I suspect that the galaxies in which Tovmasjan and Bolton (cf. Paper 63) observed emission from the nuclear

regions only, are not 'normal' galaxies but are, to some extent, radio-galaxies, perhaps of the NGC 1068 type with slightly enhanced radio emission. May we have clarification on this point, please?

H. M. Tovmasjan answers: The radio indices of these galaxies do not differ more than 2 or 3 magnitudes from those of normal galaxies, so they are related rather to the normal galaxies than to the radio-galaxies. The observed galaxies of course do differ from our own Galaxy, which has no such enhanced radio emission in its nuclear region.

S. B. Pikel'ner: I agree with Ginzburg (Paper 61) that absence of a radio halo does not prove the absence of a physical halo. Moreover, we do observe the lower parts of the halo: the radio disk is thicker than the spiral arms, especially in the central region of the Galaxy. The radio emission shows that there is a rather high pressure of cosmic rays and of the magnetic field outside the spiral arms, where the gas density is low. If the density gradient in the halo is strong, the pressure of cosmic rays can not be balanced by the gas and some kind of expansion or instability should develop. In a quasi-stable system, the densities of gas and cosmic rays and the magnetic pressure should smoothly decrease outwards. So the thickness of the halo should be much larger than that of the observed radio disk.

3. ANNIHILATION AS ENERGY SOURCE

H. Alfvén: I will say a few words about energy sources, and I confine myself to the most energetic source, namely annihilation. This is in connection with the discussion which started recently about the possible existence of antimatter in the Universe. I think everybody would very much like to have a certain degree of symmetry in the Universe between matter and antimatter, from a more philosophical point of view, but as soon as one tries to introduce this into the realm of astronomy, everybody objects; apparently we should like to have antimatter in the Universe, but very far away, so that you need not take any account of it.

Now one may ask: 'Is there any possibility that there is antimatter in such a way that it would be of interest from an astronomical point of view? Could, for example, a very distant galaxy consist of antimatter instead of matter; would there be any obviously observable phenomenon which is against this? If there is, say, a galaxy or any celestial object consisting of matter, and in another region we have another celestial object consisting of antimatter, we would not distinguish between these by looking upon them, because the light is exactly the same. The Zeeman effect certainly is reverse for antimatter, but we cannot distinguish between matter with a magnetic field in this direction and antimatter with a field in the opposite direction, for we have no independent way of deciding about the magnetic field. Consider now a region of celestial objects of this kind, surrounded by some matter, and an antimatter object surrounded by intergalactic antimatter; then there would be a region where these interact, and one would at first think that there would be a very strong release of energy. This is not at all certain, however, because a very thin sheath may form, separating matter and antimatter, and the radiation from an interface of this kind would not be very strong.

From this we can conclude that there is no phenomenon observed by us which would be against the assumption that, for example, the Andromeda Nebula or any other galaxy would consist of antimatter. But if we go one step further and ask ourselves whether

there could be antimatter within our Galaxy, we reach a rather shocking result. I am not at all proposing that there is any definite proof that we have antimatter in our Galaxy, but it is surprising to find that there is no argument for the view that the celestial objects in our Galaxy consist of ordinary matter, except of course the solar system. We can, by definition, say the Earth consists of matter; and one can easily find that all the bodies in the solar system consist of ordinary matter. But if we turn to, say, any star in the sky, what arguments are there for assuming that it consists of ordinary matter and not of antimatter? I must confess I am not aware of any decisive argument.

If therefore inside our Galaxy we have antimatter, there should be regions in which matter and antimatter mix, and it is of interest to see what that will produce. If we have a proton and an antiproton annihilating, they will yield an energy of $2\,m_{\mathrm{p}}\,c^2$; they will give a neutrino which takes one half of the energy, and gamma-rays which take one third of the energy, and positrons and electrons which together take about one sixth of the total energy. The neutrinos cannot be observed very well. The gamma-rays have an energy in the region of a few hundred MeV. The electrons and the positrons form a continuous spectrum with a maximum at about 50 MeV and quite appreciable numbers of electrons up to 100 MeV. These particles will spiral in the magnetic fields, with synchrotron radiation as a result; and they will also be absorbed in matter in general, so there will be bremsstrahlung.

We conclude that, if there is matter and antimatter within our Galaxy, there should be regions where both are mixing; they will give neutrinos, which cannot be observed, and gamma-radiation, which is rather difficult to observe. The synchrotron radiation is easiest to observe, and next comes the bremsstrahlung, which will not be very easy to detect. The cause of this is that radio-astronomers are 10^7 times cleverer than nuclear physicists concerning the detection of radiant energy. You must have synchrotron radiation which is 10^7 times the limit of detectability before you get so much gamma-radiation from it that you can detect it. Therefore, synchrotron radiation is the best indication of annihilation energy, but of course there are also other ways of generating synchrotron radiation.

Oort: How can one distinguish between these mechanisms? Do you have any suggestions?

Alfvén: Yes, I have quite a few. But we should have a little coffee first.

REFERENCES

Cline, T. L., Ludwig, G. H., McDonald, F. B. 1964, *Phys. Rev. Lett.*, **13**, 786.

Daniel, R. R., Stephens, S. A. 1966, in *Proceedings Ninth International Conference on Cosmic Rays* (London, September 1965), Ed. A. C. Stickland, Vol. 1, publ. by the Institute of Physics and the Physical Society, London, p. 335.

Ginzburg, V. L., Syrovatskij, S. I. 1964, *The Origin of Cosmic Rays*, Pergamon Press, Oxford.

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Chapter III E

X-Rays in the Galaxy

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'We have such a large amount of gravitational energy in such a binary system; we must use it! Of course!'
V. L. Ginzburg, in the Discussion (Paper 79)

75. RECENT ADVANCES IN X-RAY ASTRONOMY*
(Introductory Report)

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ABSTRACT

In a review written in December 1965, the author of this report has summarized the state of observational X-ray astronomy at that time. Further data that have become available since then have produced important advances in several directions. New sources have been discovered, some of which have been tentatively identified with known galactic or extragalactic objects. Evidence has been presented for variability of the X-ray flux received from at least one of the sources. New spectral information has been obtained. New observations of the strong X-ray source in Scorpius, Sco X-1, have greatly reduced the previous upper limit for its angular size and have provided a much more accurate determination of its celestial coordinates. This determination has led to the identification of Sco X-1 with a faint visible object whose peculiar properties had, until then, escaped the attention of astronomers.

Introduction

Recent months have witnessed significant advances in X-ray astronomy. The most important results include:

(1) the discovery of new sources and their tentative identification with optical objects;

(2) evidence for variability of at least some X-ray sources;

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(3) new information on X-ray spectra;

(4) a new and considerably more precise determination of the angular size and of the location of the strong source in Scorpius, and the consequent identification of this source with a 'peculiar' visible object.

All of these results were obtained by means of rocket- and balloon-borne instruments. To my knowledge no observation of X-ray sources other than the Sun has been carried out as yet by means of satellites, although it is expected that both manned and unmanned satellites will be used for X-ray astronomy in the not too distant future.

I propose to summarize here the highlights of the observational data released since the beginning of 1966, leaving out experimental details that may be found in the original papers listed in the bibliography.

1. NEW SOURCES

In a review paper (Rossi 1966) completed in December 1965, I have listed the X-ray sources known at that time. Of these sources, only one had been identified with an object previously known from optical or radio observation; this is the well-known source Tau XR–1, which coincides with the Crab Nebula (Tau A). The location of the other sources is shown in Figure 1. These include Sco X–1, the strongest extra-solar X-ray source, whose discovery (Giacconi *et al.* 1962) marked the beginning of X-ray astronomy. They further include two sources in the constellation of Cygnus, a likely source in Serpens, and a complex of at least six sources near the galactic equator, within about 20° of the galactic center. There was (and there still is) some uncertainty concerning the number and location of the sources in this complex. None of them, however, seems to coincide with any of the peculiar objects known in this region, such as Sagittarius A (the radio center of the Galaxy) and SN 1604 (the remnant of Kepler's Supernova).

Table 1

Positions and intensities of X-ray sources (cf. Figure 2)

Code	Name	Right ascension	Declination	Relative intensity
A	Sco X–1	16^h 17^m	$-15.^{\circ}5$	100
B_1	Sco XR–2	17 08	−36·4	7·5
B_2	Sco X–2	16 50	−39·6	7·5
C	Sco XR–3	17 23	−44·3	6
D	Tau XR–1	5 31·5	+22·0	15
E	Oph XR–1	17 32	−20·7	7
F_1	Sgr XR–1	17 55	−29·2	8·5
F_2	Sgr X–1	17 44	−23·2	8·5
G	Sgr XR–2	18 10	−17·1	8
H	Ser XR–1	18 45	+ 5·3	4
I	Cyg XR–1	19 53	+34·6	19–5
J	Cyg XR–2	21 43	+38·8	4
K	Cyg XR–3	19 58	+40·5	2
L	Cyg XR–4	21 21	+44	1·5
M	Leo XR–1	9 35	+ 9	1
N	Cas A?	23 21	+58·5	1·5
O	Vir A?	12 28	+12·7	1

Sources of data: Byram *et al.* (1966), Bowyer *et al.* (1965), Clark *et al.* (1965).

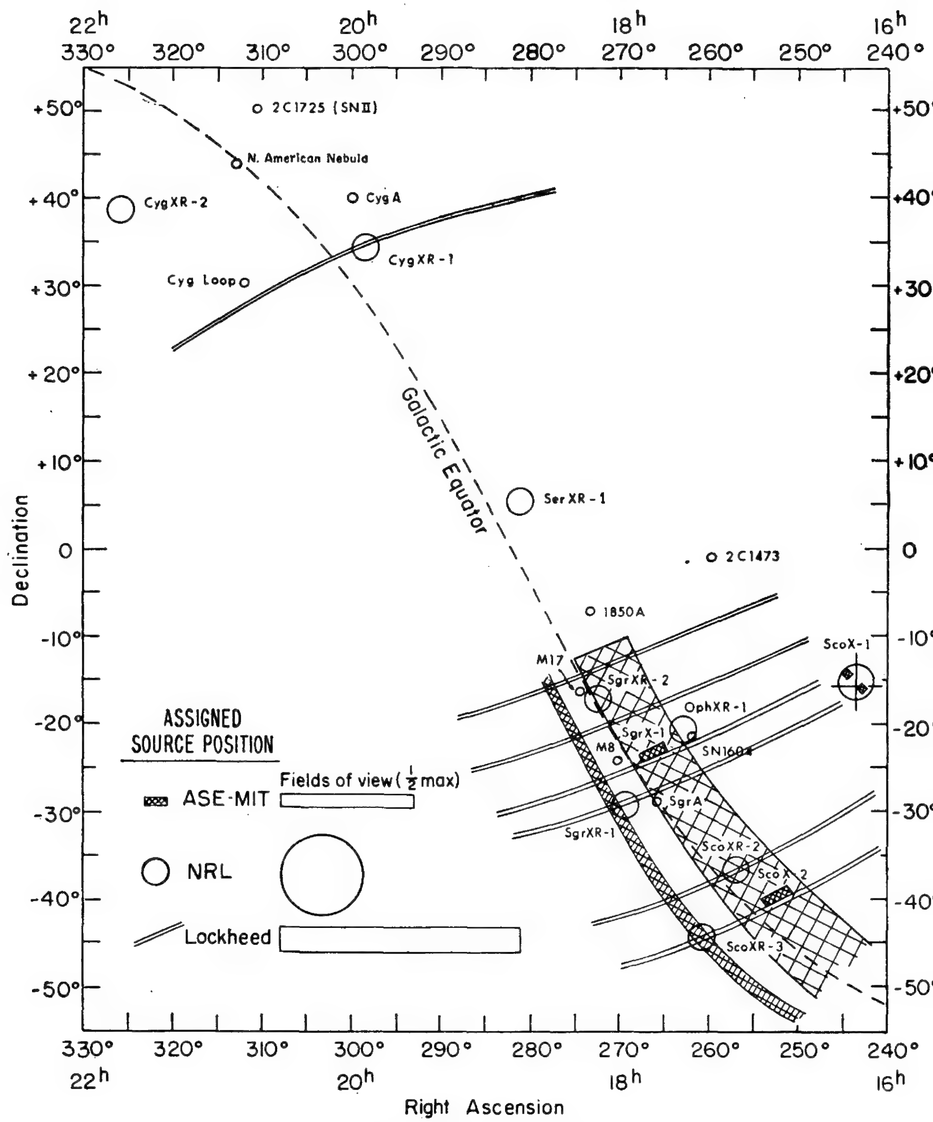

FIG. 1. X-ray sources near the galactic center and in the Cygnus region, known at the end of 1965 (Rossi 1966).

Figure 2 and Table 1 show the sources that appear to be best established among those known at present. The additions to the previous map result from an analysis by Friedman's group (Byram *et al.* 1966) at the Naval Research Laboratory (NRL) of the data obtained during their rocket flight of April 1965. As on previous flights, the NRL group used a honeycomb collimator, with an angular transmission curve of about

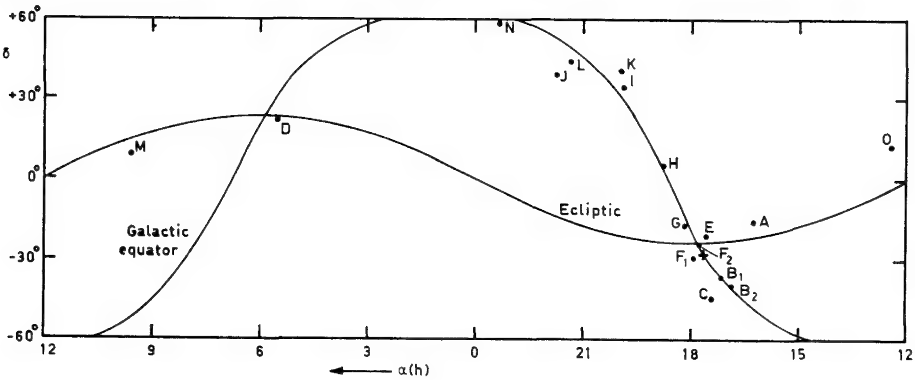

FIG. 2. Location of X-ray sources known as of June 1966. For numerical data see Table 1.

8° width at half-maximum. The estimated error circle for the position of the observed sources had a radius of about 1°5.

Of the new sources one has a position consistent with that of *Cas A*, believed to be a type-II supernova remnant at an estimated distance of about 3·4 kpc. The observed flux in the 1 to 10Å range is about 4×10^{-9} erg cm^{-2} sec^{-1}. For the assumed distance of 3·4 kpc, the emitted power turns out to be about 5×10^{36} erg sec^{-1}, which is similar to that of the Crab Nebula. If the identification is correct, the X-ray emission of Cas A is about 15 times greater than the radio emission; for the Crab Nebula the corresponding ratio is 450.

The circle of uncertainty for another new source includes *M 87*, a bright elliptical galaxy in the Virgo Cluster. The estimated mass of this galaxy is about ten times that of our own, its estimated distance is about 11 Mpc. A well-known feature of M 87 is a jet, about 1000 pc long, emitting polarized light via the synchrotron mechanism. If the identification is correct, the X-ray emission of M 87 in the 1 to 10Å range amounts to about 3×10^{43} erg sec^{-1} (as computed from the assumed distance and from an observed flux of about 2×10^{-9} erg cm^{-2} sec^{-1}). For this source, the power in the X-ray band is about 100 times greater than the power in the radio band, so that, as noted by Ginzburg, the object should be called an *X-ray galaxy* rather than a radio galaxy.

Several new sources were found in the Cygnus region. Figure 3 shows the scans performed in this region during the NRL flights of April 1965 (solid lines) and June 1964 (dashed lines). Two of the 1965 scans (b and e) passed close to Cyg XR–1 as well as to the extragalactic radio source *Cyg A*. The counting rates observed in these scans are illustrated in Figure 4. Both curves display strong, asymmetric peaks due presumably to the unresolved effects of two sources lying close together. Within the experimental uncertainties, one may account for the shapes of the peaks by assuming that one of the sources is the same as Cyg XR–1, discovered in the 1964 survey, while the other (Cyg XR–3) is coincident with Cyg A. To recall well-known facts, Cyg A, the brightest extragalactic radio source, has been identified with an optical galaxy consisting of two separate condensations, about 2″ (arc) apart. The radio emission comes from two vast regions, with their centers separated by about 100″ (arc). The estimated distance of Cyg A is 220 Mpc. If the identification is correct, one finds that the X-ray emission of

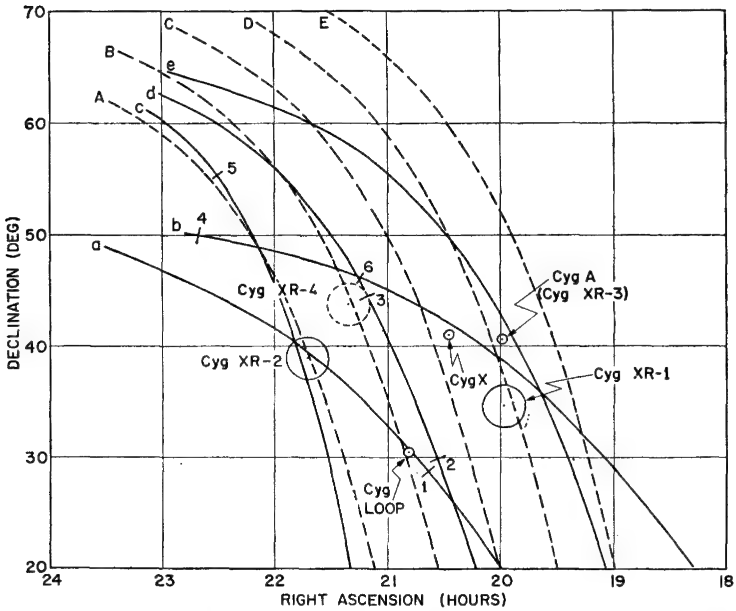

FIG. 3. Scans through the Cygnus region, made during the NRL flights of June 1964 (dashed lines) and April 1965 (solid lines; see Byram *et al.* 1966).

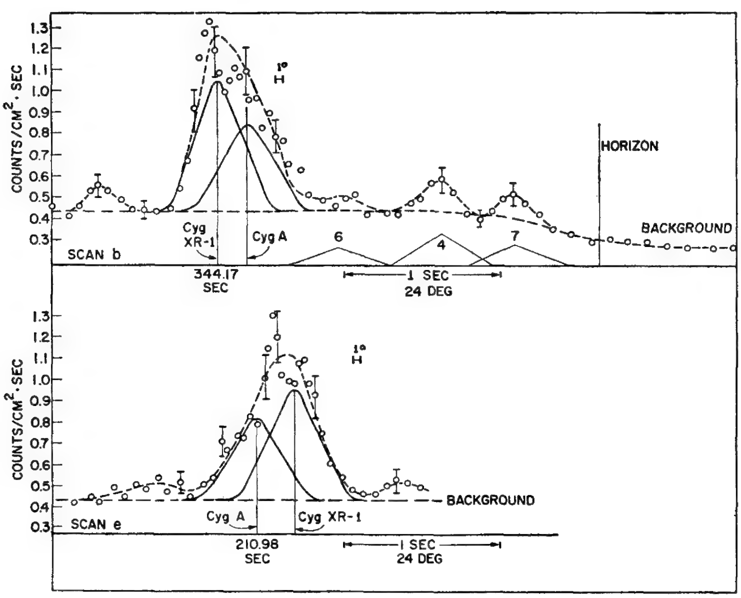

FIG. 4. Evidence for an X-ray source coincident with Cyg A (Byram *et al.* 1966).

Cyg A is about 45 times its radio emission so that this object, too, would deserve the name of an X-ray galaxy. The absolute value of the X-ray emission (as estimated from the assumed distance and from an observed flux of about 4×10^{-9} erg cm^{-2} sec^{-1}) amounts to about 2×10^{46} erg sec^{-1}.

As is stressed by the authors, all of the above identifications, and particularly that of the unresolved X-ray source Cyg XR–3, are only tentative, because of the comparatively large area of uncertainty for their location.

Another new source clearly detected in the NRL 1965 survey in the Cygnus region lies within the circle marked *Cyg XR–4* in Figure 3. No identification with optical or radio objects has been suggested. There appears to be still another weak source in Cygnus near the points marked 1 and 2; this location is close to the center of the Cygnus Loop, but does not seem to coincide with it.

A number of weaker sources are indicated by small peaks in the counting-rate curves. Some lie again in the Cygnus region, one in the constellation of Leo (*Leo XR–1*). Moreover, according to the NRL observations the unresolved X-ray background, which was detected in all X-ray flights, 'shows a degree of random variations indicative of many unresolved discrete sources'.

Finally it deserves mention that a partially successful rocket flight by the Lockheed group in September 1965 appears to have detected two additional sources in the region near the galactic equator, at about 14° and 340° galactic longitude respectively (Fisher *et al.* 1967).

2. VARIATIONS WITH TIME

The case for variability of the X-ray emission of sources other than the Sun has been presented most forcefully by the NRL group on the basis of a comparison between their observations made in June 1964 and in April 1965. After correction for possible differences in sensitivity between the detectors used in the two flights, the intensity of Cyg XR–2 appeared to be unchanged; however, Byram *et al.* (1966) found the intensity of *Cyg XR–1* to have decreased by a factor of four from the time of the first flight to the time of the second. Indeed it was apparently the considerable decrease in brightness of Cyg XR–1 that made possible the detection of the nearby source Cyg XR–3 during the 1965 flight. Presumably at the time of the 1964 flight the signal from Cyg XR–3 had been completely masked by the then much stronger signal from Cyg XR–1.

There are other indications for variability of Cyg XR–1, although, coming as they do from observations made by different groups with instruments of different design, they are less definite than that presented by the NRL group. Thus the X-ray flux from this source observed by the Lockheed group, in a rocket flight carried out in October 1964, was about five times smaller than that observed by the NRL group in June of the same year. However, Fisher *et al.* (1966) tentatively attributed this to a difference in the spectral response of the detectors used in the two flights. Similarly, two rocket flights carried out by scientists at the Lawrence Radiation Laboratory (LRL) in June 1965 and October 1965 gave for Cyg XR–1 a much smaller X-ray brightness than that observed by the NRL group in June 1964 (Chodil *et al.* 1965, Grader *et al.* 1966).

Sco X–1 may also have a variable brightness. The ASE* group, on the basis of a rocket flight carried out in October 1964 (Giacconi *et al.* 1965), found the X-ray flux

* American Science and Engineering.

from this source, in the spectral region from 1 to 10 keV, to be $(1{\cdot}6 \pm 0{\cdot}4) \times 10^{-7}$ erg cm^{-2} sec^{-1}. The Lockheed group (Fisher *et al.* 1966) reported a similar flux value. On the other hand, the data obtained by the LRL group during the two rocket flights mentioned above, when reduced to the same spectral region, gave fluxes of about 5×10^{-7} erg cm^{-2} sec^{-1}. What I shall have to say about Sco X–1 in Section 5 may have some bearing upon the possible variability of this source.

Finally I may mention that certain observations suggest a possible variability, not only in the intensity but also in the shape of the *spectrum of Tau XR–1* (see Section 3*b*).

3. SPECTRAL MEASUREMENTS

The information available in December 1965 has been supplemented by the publication of new data obtained from several balloon and rocket flights.

The new measurements, like the previous ones, are based on pulse-height distributions of proportional counters or scintillation counters. The energy resolution is typically of the order of 30% and is thus not sufficient for the detection of possible lines, unless these are widely separated and sufficiently strong compared with the continuum. Since Tanaka discusses spectral measurements of both discrete sources and the unresolved background (Paper 76), I shall limit myself to some brief remarks concerning Sco X–1 and Tau XR–1 (the Crab Nebula).

(*a*) *Sco X–1*

For $h\nu \gtrsim 2$ keV, the results of the various groups are consistent with exponential spectra of the type

$$I(E)\,\mathrm{d}E = \text{const. } \exp\,(-h\nu/kT)\,\mathrm{d}(h\nu) \text{ erg cm}^{-2}\text{ sec}^{-1},$$

such as is expected for the bremsstrahlung from a hot, optically thin cloud of fully ionized gas. The values of kT and T obtained by the various experimenters, and the spectral ranges in which they were measured, are listed in Table 2. The two first lines (starred) refer to results already available in December 1965. The differences in the values of T are within the experimental uncertainties. However, as already noted, there is no good agreement concerning the absolute flux.

Table 2

Temperatures determined from X-ray spectrum of Sco X–1

Reference	Group	Spectral range (keV)	kT (keV)	T (10^6 °K)
*Giacconi *et al.* (1965)	ASE	1–15	$3{\cdot}3 \pm 1{\cdot}6$	38 ± 18
*Chodil *et al.* (1965)	LRL	2–20	5	58
Grader *et al.* (1966)	LRL	2–20	4	46
Peterson and Jacobson (1966)	La Jolla	18–50	4·3	50

Although, as mentioned above, an exponential spectrum is characteristic of the bremsstrahlung from an optically thin cloud, other emission mechanisms are not yet ruled out. For example, it has been noted by Manley (1966) that the synchrotron radiation produced by electrons whose energy distribution falls sharply to zero above a given value of the energy, may have a nearly exponential spectrum. On the other hand,

it is important to point out that one cannot fit the data obtained in different energy ranges to a single Planck spectrum, such as expected from a hot, optically thick body.

Measurements by the LRL group (Grader *et al.* 1966) seem to indicate a drop in the differential spectrum below 1·5 keV. However, because of possible systematic errors, the authors do not regard this result as firmly established. In connection with the low-energy part of the Sco X–1 spectrum, I wish also to mention a still unpublished result of the NRL group, which Friedman has kindly allowed me to quote. From a comparison between the counting rates of various counters, some of which had a low-energy 'window' starting at the K-edge of carbon (44 Å), the NRL scientists concluded that the observable spectrum of Sco X–1 extends to this spectral region, i.e., to energies less than 300 eV. In fact the data appear to indicate that, in the low-energy X-ray region, the spectrum rises faster with decreasing energy than an exponential distribution.

(*b*) *Tau XR–1*

For this source the results of different groups appear to give not only different absolute intensities, but also different spectral shapes. For example Peterson *et al.* (1966) find that all their measurements from 16 to 120 keV may be fitted to a single power-law spectrum,

$$I(E)\,\mathrm{d}E = \text{const.}\, E^{-\alpha}\,\mathrm{d}E,$$

with $\alpha = 1$. However, other observers such as Clark (1965) and Haymes and Craddock (1966) find that the spectrum cuts off sharply above 10 or 20 keV. Also, their spectra below this energy are steeper than that obtained by Peterson *et al.* More measurements will be needed before this apparent disagreement is cleared up. One possibility which has been suggested, and which deserves further investigation, is that the spectrum of Tau XR–1 may change with time. In this connection I should like to mention that, if the X-ray source in the Crab is due to the same synchrotron process which is also responsible for the radio and visible emission, a power-law distribution for the electrons, with a high-energy cut-off varying in time, may provide an explanation for the indicated changes in the X-ray spectrum (Manley 1966).

4. ANGULAR DIMENSIONS, LOCATION AND IDENTIFICATION OF SCO X–1

The new data on the angular size and the location of Sco X–1 were obtained in one of the rocket flights that are part of the American Science and Engineering (ASE) program in X-ray astronomy under the direction of Riccardo Giacconi. In this, as in some previous flights, the ASE group had the collaboration of the MIT group, whose senior member was Minoru Oda, on leave from the University of Tokyo. Herbert Gursky had the main responsibility for the ASE part of the program.

(*a*) *Instrumentation*

The vehicle used was an attitude-controlled rocket, and the flight took place in March 1966. The instrumentation of this rocket represents a qualitative advance over previous techniques of X-ray astronomy. The improvement regards both the angular resolution of the X-ray detector, and the accuracy in the determination of its instantaneous orientation with respect to the stars.

The ***angular resolution*** was achieved by means of a modified version of the modulation

collimator originally developed by Oda, which combines a wide field of view with a fine resolving power. The rocket contained two separate collimators of this type. Each collimator was made of a series of parallel grids; its angular response consisted of a series of transmission bands, about 40″ (arc) wide at half-maximum, separated by distances of about 5′ (arc). The radiation was detected by beryllium-window proportional counters sensitive in the spectral region from about 2 to about 20 keV, placed behind the collimators.

The axes of both collimators were parallel to the longitudinal axis of the rocket. The attitude-control system pointed this axis in the general direction of Sco X–1, and then allowed it to drift slowly. Since the collimators have a fine angular resolution only in the direction perpendicular to the wires, the rocket was programmed to roll about its longitudinal axis at some time during the flight, so as to provide angular information in different directions.

The accurate *determination of the instantaneous orientation* of the collimators' axes was achieved by the inclusion in the payload of a photographic camera which, during the flight, took pictures of the sky at one-second intervals. To eliminate the possibility of systematic errors that might result from a slight change at take-off in the orientation of the optical axis of the camera relative to the axes of the X-ray collimators, a diffuse light source was arranged in such a way that the star field and the transmission bands of the collimators appeared in the same frame. In this manner it was possible to determine the precise position of the transmission bands at the times when maxima of the transmitted X-ray intensity were observed.

There remained an uncertainty as to which of the transmission bands actually contained the X-ray source. This uncertainty was greatly reduced by the use of a 'vernier' method, suggested by Gursky, and based on a 5% difference in the separation between the transmission bands of the two collimators.

(*b*) *Angular dimensions of Sco X–1*

Not much elaboration of the data was needed to obtain the desired information concerning the *angular size* of Sco X–1. A plot of the counting rates against time showed a series of narrow peaks, due to the drift of the X-ray source across the transmission bands of the collimators. Figure 5 gives an example of such records. In Figure 6 the data corresponding to several peaks are superposed to improve the statistical accuracy, and the resulting observed variation of the counting rate is compared with that computed for a point source. The agreement is as good as one might expect, considering the unavoidable small imperfections of the collimator and the uncertainties in the superposition of the different peaks.

On the basis of this result, Gursky *et al.* (1966*a*) announced in April 1966 that the angular dimensions of Sco X–1 cannot exceed 20″. As a comment on the observational technique, it is of some interest to note that the angular resolution achieved in this flight compares favorably with that achieved by the NRL group in their well-known measurement of the angular size of the X-ray source in the Crab Nebula by the lunar-occultation method.

The previous upper limit for the size of Sco X–1, obtained by the same ASE-MIT group, was 7′. The new upper limit—20 times smaller in linear dimensions, 400 times smaller in area—brought to a sharper focus the problem of explaining the absence of

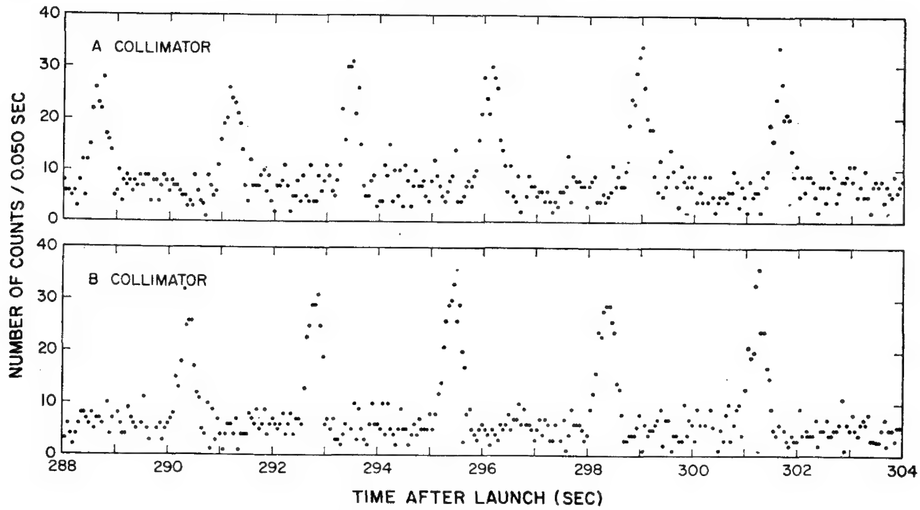

FIG. 5. Counting rates vs. time for the two detectors flown by the ASE-MIT group in March 1966.

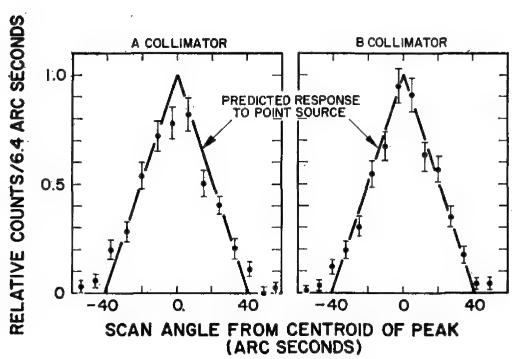

FIG. 6. Superposition of several peaks, showing that the observations of Sco X–1 are consistent with a point source.

any conspicuous visible object in the general direction of the strong X-ray source. This is an important point which deserves some comment.

As already mentioned, the X-ray spectrum of Sco X–1 does not fit that of a black body, and strongly suggests an emission process (probably bremsstrahlung from a hot gas, possibly synchrotron radiation) occurring in a medium transparent to its own radiation. In this case one should expect that the power emitted per unit frequency interval increases, or at least remains approximately constant, with decreasing frequency. From the observed X-ray flux (taken as $1{\cdot}6 \times 10^{-7}$ erg cm^{-2} sec^{-1}), one can then conclude that, apart from interstellar absorption (which is not very important in the direction of Sco X–1, see below), the visible radiation from this source should be at

least equivalent to that of a 13th-magnitude star. Now if this light flux were diluted over a disk of several minutes of arc diameter, the surface brightness would fall below the limit of detectability. In fact, it had been suggested that Sco X–1 might be the remnant of an ancient and relatively nearby supernova, whose core had sufficiently expanded to become invisible. However, a 13th-magnitude object of 20″ diameter or less is well above the visibility limit. And yet no nebulosity of the expected brightness could be found in the region of Sco X–1. Gursky *et al.* (1966*a*) thus concluded that, in all likelihood, the visible counterpart of this X-ray source was a *star-like object*, of about 13th magnitude.

(*c*) *Location*

In the direction of Sco X–1 there are about 100 stars of 13th magnitude or brighter per square degree. Thus, for a positive identification of Sco X–1 with a visible object, it was essential to determine its position within a small fraction of one square degree. The rocket flight that I have described provided the data needed for this determination. However, the task of extracting from these data the *exact position* of Sco X–1 was much more difficult and time-consuming than the task of determining its angular size. The analysis has been completed recently and I am indebted to the authors for permission to quote their, still unpublished, results at this Symposium*. These results yield two, a priori equally probable, locations for Sco X–1, defined by the following coordinates:

$$\alpha = 16^{h}\,17^{m}\;\;7^{s} \pm 4^{s}, \qquad \delta = -\,15^{\circ}\,30'\,54'' \pm 30''; \text{ and}$$

$$\alpha = 16^{h}\,17^{m}\,19^{s} \pm 4^{s}, \qquad \delta = -\,15^{\circ}\,35'\,20'' \pm 30''.$$

The areas of uncertainty corresponding to the two locations are indicated by the two rectangles at the center of the inset in Figure 7. This figure also shows two additional rectangles, representing possible, but a priori much less likely, locations for the source. The combined area of the two preferred rectangles is only four square arc minutes, or about 1/1000 of a square degree. The new locations are $0\overset{\circ}{.}5$ or more from those reported earlier. I should like to add that the overall accuracy of the method was checked by an observation, during the same flight, of the Crab Nebula. This observation was of lower accuracy than those obtained for Sco X–1, largely because of the much smaller strength of the source Tau XR–1. Yet the area of uncertainty for the location of the latter X-ray source was found to consist of four narrow bands, one of which passes through the visible nebula.

(*d*) *Identification*

Preliminary results on the location of Sco X–1 (which turned out later to be very close to the final results that I have quoted above) were made available last June to Oda (who had returned to Japan), and, through him, to the staff of the Tokyo Observatory, as well as to Sandage and his colleagues at the Mount Wilson and Palomar Observatories.

With this new knowledge of the position, both groups undertook a joint search for the visible counterpart of Sco X–1. As noted above, one expected this to be a star-like object of about 13th magnitude. Moreover, it should have an essentially flat spectrum in the visible and ultraviolet regions, and therefore should appear much more 'blue' than ordinary stars. The search has been successful, and the Palomar, Tokyo, ASE

* The work has since appeared in print: Gursky *et al.* (1966*b*).

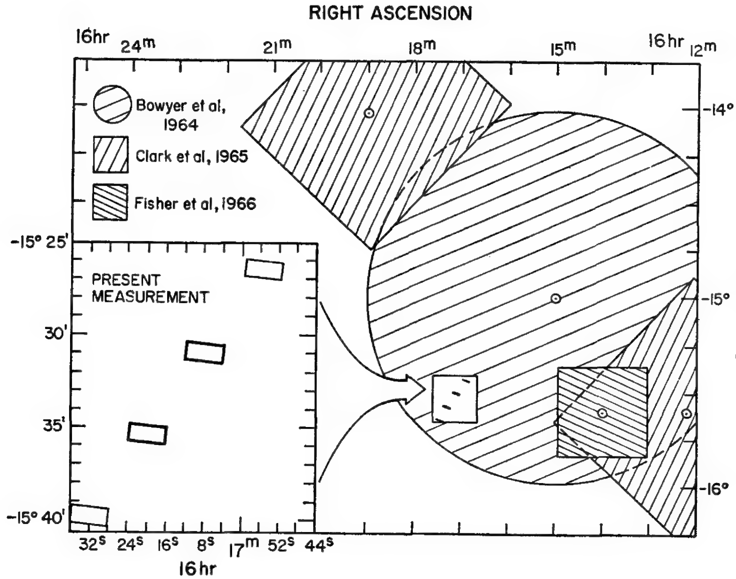

FIG. 7. Location of Sco X–1 as obtained from the ASE–MIT flight of March 1966.

and MIT groups are jointly submitting its results for publication (Sandage *et al.* 1966). Again I am indebted to the authors for permission to communicate these unpublished results at the Symposium.

A two-color plate (one image in the blue, one in the ultraviolet) was taken at Tokyo Observatory in the night of 1966 June 17–18. It revealed the existence of an intense *ultraviolet object* of visual magnitude 13 near the center of the search area. Photoelectric photometry confirmed this result and showed that the spectrum is essentially flat in the visible, so that the object appears much more 'blue' than ordinary stars. A spectrogram taken on June 18–19 gave a continuous spectrum, with no absorption features, but with faint emission lines.

On June 23, photoelectric observations with the 200-inch Palomar reflector confirmed these results. Moreover they showed that the visible light flux from the object varies irregularly by a few per cent in several minutes.

A second, improved spectrogram taken at Tokyo Observatory on June 25–26 clearly showed the emission lines of H and He against a 'blue' continuum.

The position of the object was measured at both Tokyo and Palomar Observatories. The result was:

$$\alpha = 16^{\mathrm{h}}\ 17^{\mathrm{m}}\ 4\overset{\mathrm{s}}{.}3, \qquad \delta = -\ 15^{\circ}\ 31'\ 13''.$$

Figure 8 is a photograph of the sky, showing the object in question (arrow) and the two most likely positions for the X-ray source (each surrounded by a rectangle of 2′ by 1′ (arc) corresponding to the observational uncertainty). The object is about 40″ (arc) away from one of the most likely positions.

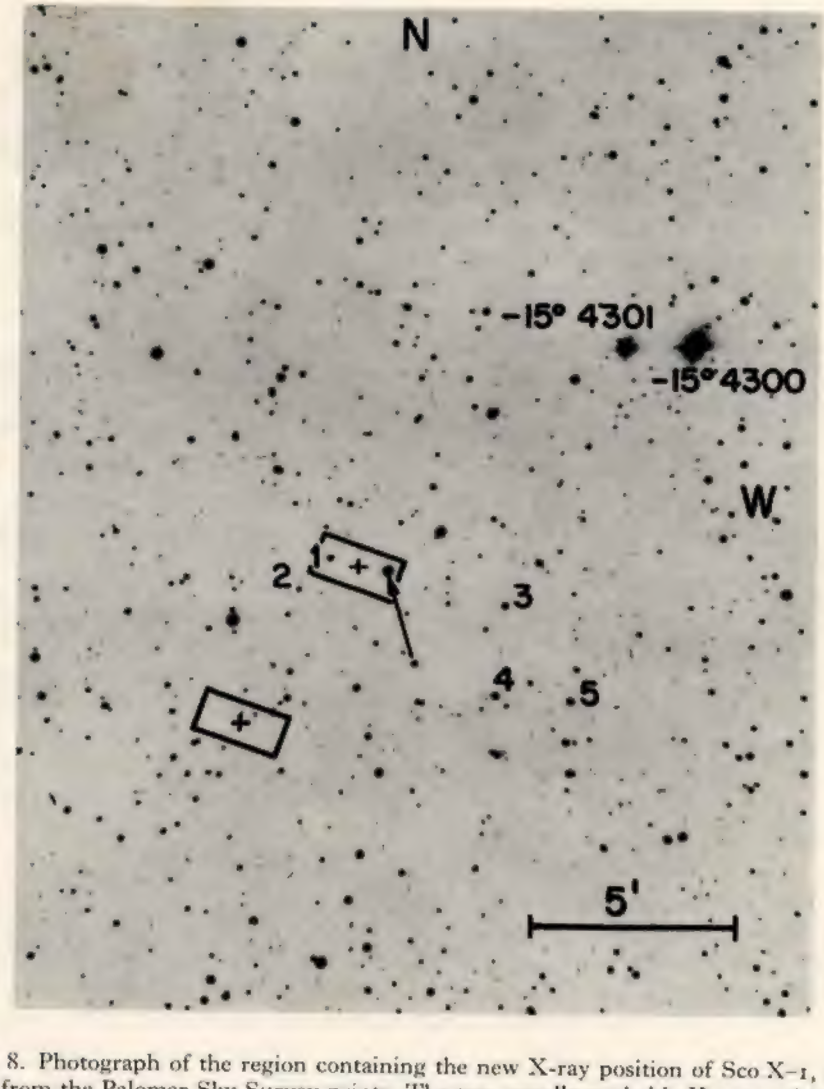

FIG. 8. Photograph of the region containing the new X-ray position of Sco X–1, reproduced from the Palomar Sky Survey prints. The two equally probable X-ray positions are marked by crosses surrounded by rectangles of 1′ by 2′ (arc). The arrow points to the very blue 13th-magnitude star which probably is to be identified with the X-ray source.

Thus an object of the predicted brightness and with the predicted color characteristics was indeed found within the very small area of uncertainty for the position of the X-ray source. It was natural to conclude, as the authors did, that this object is the visible counterpart of Sco X–1.

I feel that the chances of a mistaken identification are exceedingly slim. In the first place, while the a-priori probability of finding a star of 13th magnitude or brighter within an area of 4 square arc minutes is 1/10, the probability of finding a 'blue' object of this magnitude within the same area is many orders smaller. In the second place, no other candidate is available. The next brightest object within the area of uncertainty has magnitude 15, and has the appearance of a normal star. A search for 'blue' objects conducted at Tokyo Observatory has failed to detect any within a circle of $0^\circ.5$ radius around the position of Sco X–1. In order to determine whether the visible counterpart of Sco X–1 might possibly be obscured by interstellar absorption, observations were made at Palomar of the reddening of several main-sequence stars in the immediate neighbourhood of Sco X–1. These observations showed that, if Sco X–1 lies anywhere between 100 and 400 pc, interstellar absorption in the visible amounts to only 0·7 magnitudes. Thus a mistaken identification would require: (1) that Sco X–1 is invisible because, against all reasonable expectation, its spectrum decreases with increasing wavelength from the X-ray to the visible region, and (2) that, by an exceedingly unlikely coincidence, an object of the expected magnitude and color characteristics happens to lie within the area of uncertainty for the position of the X-ray source.

Further photometric observations and further spectral measurements were made at Palomar Observatory in July 1966. The object was found to be highly *unstable* in its continuum radiation; it changed, on one occasion, from 12·6 to 13·2 magnitudes in a 2·6-hour period. About the spectra, I shall mention the following. The emission lines of hydrogen and He II are present, as well as high-excitation lines due to C III, N III and possibly O II. Moreover, the interstellar K-line absorption of Ca II is clearly visible. Large changes were observed both in the actual strength of the Balmer lines, and in their strength relative to the continuum.

Searching old plates of the Harvard collection, Garmire and Sreekantan succeeded in tracing the object back to 1896. During the intervening period it had undergone variations of about one magnitude around a mean value, $m = 12{\cdot}5$, without any indication of a secular trend.

5. PROPERTIES AND NATURE OF SCO X–1

Sandage noted that the properties of the visible object associated with Sco X–1, in particular the flickering activity, the long-time variations, and the spectrum, are reminiscent of those of old novae. He also noted that the overall celestial distribution of X-ray sources is similar to that of novae. He therefore suggested that many of the X-ray sources, and in particular Sco X–1, may be objects of this type.

I do not propose to discuss this particular assumption here. I should like, however, to add a few general remarks about the conclusions that may be derived from our present knowledge of the properties of Sco X–1, and about future experiments that may help to clarify the nature of the physical process responsible for its X-ray emission.

(*a*) Sco X–1 emits about 1000 times more energy in the X-ray band than in the visible band. This is comparatively much more than the Crab Nebula, or any other

X-ray source for which a tentative identification with a visible object has been suggested.

(*b*) As already noted, the nearly exponential spectrum of Sco X–1 in the energy range from 1 to 50 keV suggests a process of bremsstrahlung emission from a gas cloud at about 50×10^6 °K. If this is indeed the nature of the source (which is by no means certain), then kT is about 4 keV. This would rule out the possibility that the cloud may be gravitationally confined, except in the unlikely event that its dimensions are smaller than those of the Sun, or that it contains an object of much greater mass than the Sun. On the other hand the cloud might be contained, or at least restrained in its expansion, by a magnetic field anchored to a massive object at its center.

(*c*) It is likely that a substantial fraction of the visible continuum arises from the same process which also produces the X-ray flux, since its intensity and spectrum were correctly predicted under this assumption. On the other hand, the line spectrum must have a different origin. Indeed, if the source of the X-ray flux and of the visible continuum is a hot cloud, the spectral lines must originate in a separate, cooler region of space, for, at temperatures of the order of 5×10^7 °K, the probability of recombination into the excited states of light atoms is too small to account for the observed intensity of the lines.

(*d*) If the X-ray flux and a substantial part of the visible continuum have the same origin, it follows that the dimensions of the X-ray source are the same as those of the visible source, which from the observations is known to be less than 0″5. It also follows that the observed variability in the visible brightness is likely to be accompanied by a corresponding variability in the X-ray flux. We hope that a study of the correlation between the visible and the X-ray emissions of Sco X–1 may be included in the X-ray astronomy program by means of manned satellites, which is scheduled to begin in the near future. I may mention in this connection that Giacconi's group has already delivered an X-ray detector for installation aboard one of the early Apollo satellites. The astronaut will have the possibility of pointing the detector in any prescribed direction, and thus will be able to make repeated observations of any given X-ray source. Such correlation studies, besides providing a further test of the identification of the X-ray source with the visible object, may supply important clues on the nature of the source.

(*e*) A very important question concerns the *distance* of Sco X–1, since the distance together with the observed flux determines the energy output of the source. One piece of evidence on this matter is provided by the observations of the NRL group (Section 3), according to which Sco X–1 is detectable at wavelengths greater than 44 Å. These observations would imply that the amount of interstellar matter between the solar system and Sco X–1 cannot be more than about $1{\cdot}5 \times 10^{20}$ hydrogen atoms per cm^2, which represents unit optical thickness at 44 Å, according to Felten and Gould (1966). Taking tentatively an average density of 0·5 atoms per cm^3, we arrive at an upper limit of 100 pc for the distance. If we place the source at this distance, we find that its X-ray output in the 1 to 10 Å region is a few times 10^{35} erg sec^{-1}.

It is to be hoped that the present evidence will soon be supplemented by further data. It may be desirable to test the conclusions of the NRL group concerning the Sco X–1 spectrum beyond 44 Å, possibly by some more direct method of spectral analysis than the 'two-color photometry' used by that group. Also, one might investigate the possibility of estimating the distance of the visible object by careful measurements of its interstellar absorption lines, or by the observation of its proper motion.

I wish to conclude by stressing the fact that X-ray emission is not an isolated phenomenon, but a common property of a variety of celestial objects. These include supernovae, novae (or whatever object Sco X–1 will ultimately turn out to be) and, if the tentative identifications made at NRL are correct, radio-galaxies. For all these objects X-ray emission is energetically more important than any other radiation process. Thus X-ray astronomy is emerging as a powerful tool in a wide field of astrophysical research.

REFERENCES

Bowyer, S., Byram, E. T., Chubb, T. A., Friedman, H. 1965, *Science*, **147**, 394.

Byram, E. T., Chubb, T. A., Friedman, H. 1966, *Science*, **152**, 66.

Chodil, G. R., Jopson, R. C., Mark, H., Seward, F. D., Swift, C. D. 1965, *Phys. Rev. Lett.*, **15**, 605.

Clark, G. W. 1965, *Phys. Rev. Lett.*, **14**, 91.

Clark, G. W., Garmire, G., Oda, M., Wada, M., Giacconi, R., Gursky, H., Waters, J. R. 1965, *Nature*, **207**, 584.

Felten, J. E., Gould, R. J. 1966, *Phys. Rev. Lett.*, **17**, 401.

Fisher, P. C., Johnson, H. M., Jordan, W. C., Meyerott, A. J., Acton, L. W. 1966, *Astrophys. J.*, **143**, 203.

Fisher, P. C., Jordan, W. C., Meyerott, A. J., Acton, L. W., Roethig, D. T. 1967, in press.

Giacconi, R., Gursky, H., Paolini, F., Rossi, B. B. 1962, *Phys. Rev. Lett.*, **9**, 439.

Giacconi, R., Gursky, H., Waters, J. R. 1965, *Nature*, **207**, 572.

Grader, R. J., Hill, R. W., Seward, F. D., Toor, A. 1966, *Science*, **152**, 1499.

Gursky, H., Giacconi, R., Gorenstein, P., Waters, J. R., Oda, M., Bradt, H., Garmire, G., Sreekantan, B. V. 1966*a*, *Astrophys. J.*, **144**, 1249.

Gursky, H., Giacconi, R., Gorenstein, P., Waters, J. R., Oda, M., Bradt, H., Garmire, G., Sreekantan, B. V. 1966*b*, *Astrophys. J.*, **146**, 310.

Haymes, R. C., Craddock, Jr., W. L. 1966, *J. geophys. Res.*, **71**, 3261.

Manley, O. P. 1966, *Astrophys. J.*, **144**, 1253.

Peterson, L. E., Jacobson, A. S. 1966, *Astr. J.*, **71**, 174.

Peterson, L. E., Jacobson, A. S., Pelling, R. M. 1966, *Phys. Rev. Lett.*, **16**, 142.

Rossi, B. B. 1966, *Experimental X-ray Astronomy*, in press.

Sandage, A. R., Osmer, P., Giacconi, R., Gorenstein, P., Gursky, H., Waters, J., Bradt, H. Garmire, G., Sreekantan, B. V., Oda, M., Osawa, K., Jugaku, J. 1966, *Astrophys. J.*, **146**, 316.

NOTE ADDED IN PROOF

For more recent data on the sky distribution and variability of cosmic X-ray sources, see Friedman, H., Byram, E. T., Chubb, T. A. 1967, *Science*, **156**, 374.—*Editor*.

I.A.U. Symposium no. 31, 1967

76. SPECTRAL DATA FOR GALACTIC X-RAY SOURCES AND THEIR IMPLICATIONS FOR GAMMA-RAY OBSERVATIONS

(Invited Paper)

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ABSTRACT

The available information on the spectra of Sco X–1, Tau XR–1, Cyg XR–1 and of the background X-ray emission is summarized. Sco X–1 has an exponential spectrum; the other spectra can be represented by simple power laws. Possible mechanisms for the X-ray emission of the sources are briefly discussed.

Comparison of gamma-ray observations with extrapolations of X-ray spectra suggests that gamma-ray emitters may be found among X-ray sources. The importance of gamma-ray observations to studies of interstellar matter is stressed.

1. SPECTRA OF X-RAY SOURCES

More than 10 X-ray sources have been discovered so far. Among these we shall discuss Sco X–1, Tau XR–1 and Cyg XR–1, for which spectral measurements have been made. We shall further analyse the general background of celestial X-rays.

Figure 1 shows the spectrum of Sco X–1, as determined by Grader *et al.* (1966) and by Hayakawa *et al.* (1966). The former authors express their result by an exponential function, exp $(-E/kT)$, with $kT = 4{\cdot}0$ keV. This function can be expected for radiation from a thin, hot plasma with a temperature of about 5×10^7 °K.

Figure 2 represents the spectrum of Tau XR–1 (Grader *et al.* 1966, Hayakawa *et al.* 1966, Peterson *et al.* 1966, Haymes and Craddock 1966). There is a discrepancy in the slope of the spectrum between the balloon observations of Peterson *et al.* and those of Haymes and Craddock. However, taking into account that these results are subject to uncertain corrections for absorption and for background radiation in the atmosphere, we can reasonably well fit all points up to 100 keV by a single power law, $E^{-\gamma}$, with the exponent $\gamma = 2{\cdot}3$.

Figure 3 collects the results for the X-ray spectrum of Cyg XR–1, obtained by Grader *et al.* (1966), Hayakawa *et al.* (1966), Bowyer *et al.* (1964*a*), Byram *et al.* (1966), Fisher *et al.* (1966), McCracken (1966), and by Bleeker *et al.* (1967). Except for the observations of NRL (Bowyer *et al.*, Byram *et al.*) and of Lockheed (Fisher *et al.*), Cyg A was simultaneously in the field of view. However, its contribution is considered to be minor. Four points in the highest energy range of the spectrum of Cyg XR–1 were obtained by the Cosmic Ray Working Group in the Netherlands (Bleeker *et al.* 1967). We employed a rotating disk, which periodically masks the X-ray source from the field of

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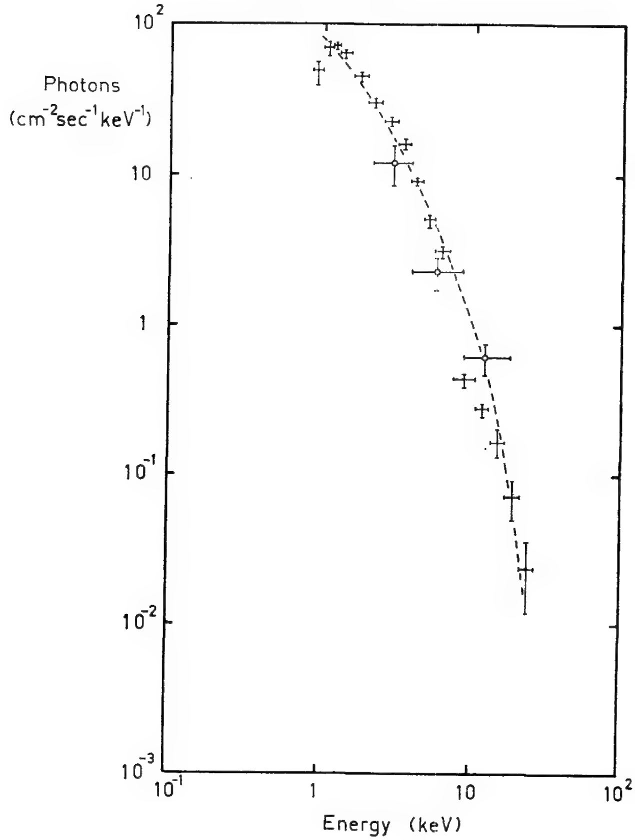

FIG. 1. X-ray spectrum of Sco X–1.

The errors of measured points are shown by error bars for both coordinates. Unmarked points: Grader *et al.* (1966); open circles: Hayakawa *et al.* (1966). The dashed line represents the exponential spectrum: $1{\cdot}2 \times 10^2 \exp(-E/kT)\,E^{-1}$ cm^{-2} sec^{-1} keV^{-1}, with $T = 5 \times 10^7$ °K.

view. This way of measurement enables us to separate unambiguously the net contribution of the source from the background. There is some trend that the spectrum flattens towards lower energies, while the high-energy part is well approximated by a power law with the exponent 2·0 as indicated in Figure 3.

Figure 4 shows the spectrum of the general background X-rays which are most likely to be of celestial origin. Results obtained by various vehicles: rockets (Hayakawa *et al.* 1966, Bowyer *et al.* 1964*a*, Byram *et al.* 1966, Fisher *et al.* 1966), balloons (Rothenflug *et al.* 1966, Bleeker *et al.* 1966), and spacecraft (Metzger *et al.* 1964), are in good agreement within the limit of errors. A power law $E^{-\gamma}$, with $\gamma = 2{\cdot}0$, gives a good fit to all points up to 1 MeV.

Consideration of the presented spectra shows that Sco X–1 differs in spectral shape

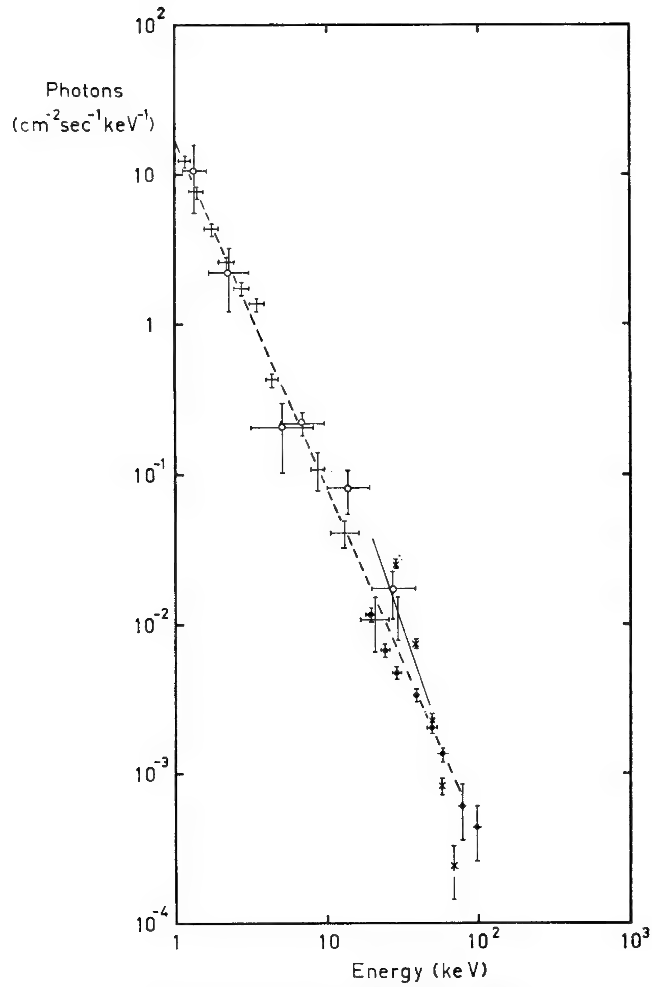

FIG. 2. X-ray spectrum of Tau XR–1.

Unmarked points: Grader *et al.* (1966); open circles: Hayakawa *et al.* (1966); dots: Peterson *et al.* (1966); crosses: Haymes and Craddock (1966). The dotted line represents the power law: $18\ E^{-2.3}$ cm^{-2} sec^{-1} keV^{-1}.

from Tau XR–1 and Cyg XR–1. The latter two sources seem to have similar types of spectra, which can be approximated by a power function. The exponent of this power law lies between 2·0 and 2·3 (the spectral index between 1·0 and 1·3), but appears significantly different in these two sources.

In view of the similarity of their spectra, we may assume that in Tau XR–1 and Cyg XR–1 the *mechanism of X-ray emission* is the same. The immediate consequences are then the following. Firstly, among the several mechanisms which produce a power-law spectrum, the inverse Compton process is not responsible for the X-rays of Tau XR–1,

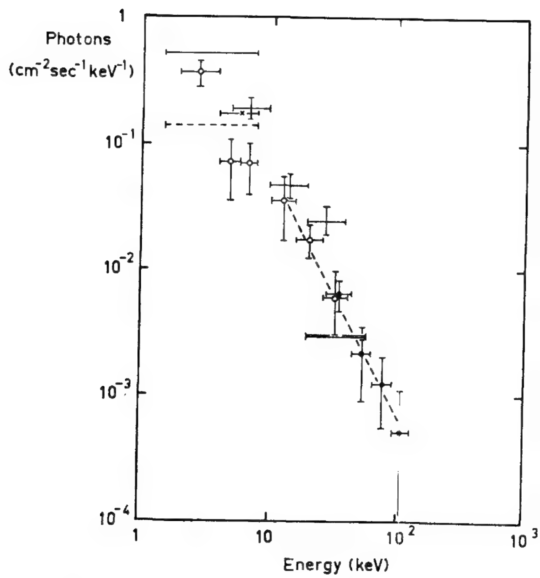

FIG. 3. X-ray spectrum of Cyg XR–1.

Open circles: Grader *et al.* (1966); unmarked points: Hayakawa *et al.* (1966); solid horizontal line: Bowyer *et al.* (1964*a*); dashed horizontal line: Byram *et al.* (1966); cross: Fisher *et al.* (1966); double horizontal line: McCracken (1966); filled circles: Bleeker *et al.* (1967). The dotted line represents the power law: $5\ E^{-2}\ \mathrm{cm}^{-2}\ \mathrm{sec}^{-1}\ \mathrm{keV}^{-1}$.

because the energy spectrum of electrons in the Crab Nebula, which is known from the radio emission of Tau A, cannot account for the observed X-ray spectrum. Secondly, synchrotron emission is not the main origin of X-rays in Cyg XR–1, since no radio source is observed at the position of this X-ray source. As a consequence, bremsstrahlung by non-thermal electrons or innerbremsstrahlung associated with the ionization of atoms are to be considered more probable mechanisms, provided that the particles have a power-law spectrum. As a possibility, Hayakawa (1966) has pointed out that if acceleration takes place in a hot plasma, the energy spectrum of electrons is no more Maxwellian, but has a tail which is expressed by a power law. A further quantitative discussion is difficult, because astronomical parameters of the sources are lacking.

2. IMPLICATIONS FOR GAMMA-RAY OBSERVATIONS

If bremsstrahlung is mainly responsible for the X-ray emission of Tau XR–1 and Cyg XR–1, there is a fair chance that the power spectrum extends to an even higher energy range, so that these two X-ray sources may appear as strong gamma-ray sources as well.

A straightforward *extrapolation of the X-ray spectra to gamma-ray energies* is shown in integral form in Figure 5. In the case of Tau XR–1, neither the upper limit set by the Explorer XI experiment (Kraushaar *et al.*, 1965) nor the improved upper limit by Cobb *et al.* (1965) reaches the probable emission range. In the Cygnus region of the

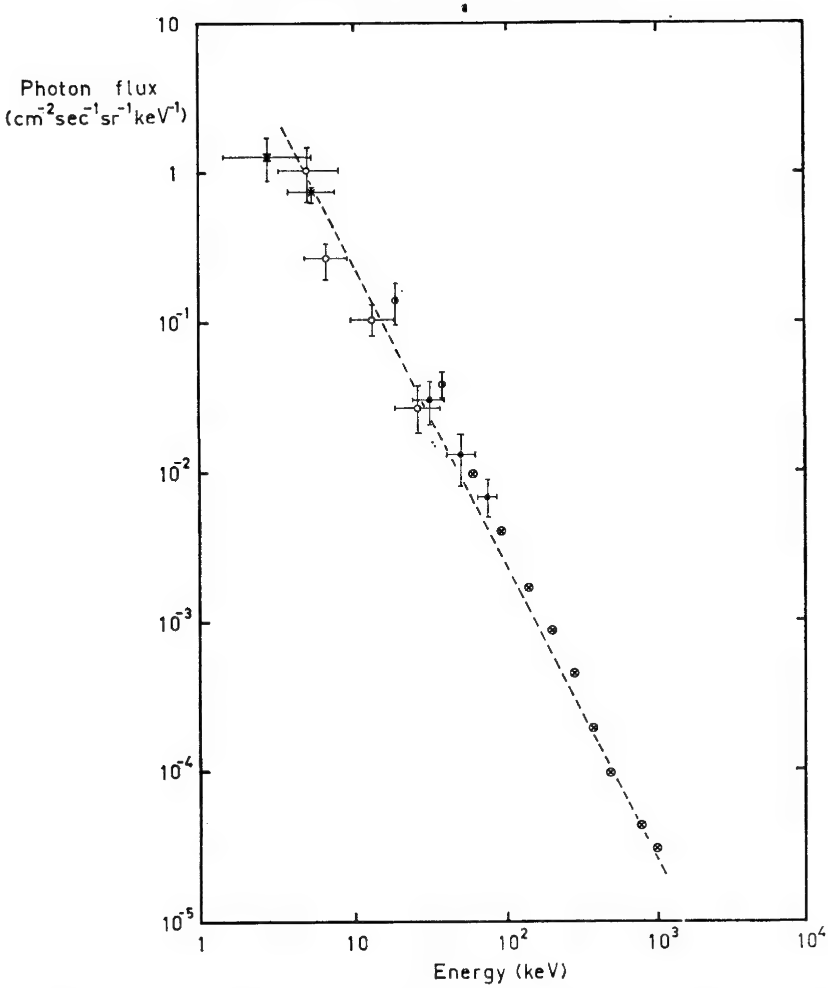

FIG. 4. Energy spectrum of isotropic celestial X-rays. Open circles: Hayakawa *et al.* (1966); double triangle: Bowyer *et al.* (1964*a*); cross: Fisher *et al.* (1966); half-filled circles: Rothenflug *et al.* (1966); filled circles: Bleeker *et al.* (1966); encircled crosses: Metzger *et al.* (1964). The dotted line represents the power law: 18 E^{-2} cm^{-2} sec^{-1} sr^{-1} keV^{-1}.

sky, recent observations by Duthie *et al.* (1966) with a balloon-borne spark chamber revealed the possible existence of a strong gamma-ray source. It is, however, unknown yet whether this source coincides with one of the X-ray sources or not. The observed gamma-ray intensity agrees with the extrapolation as shown in Figure 5.

This agreement suggests that gamma-ray sources may not necessarily be radio sources, as conventionally anticipated, but may rather be found among X-ray sources. In fact, a reasonable upper limit for the gamma-ray intensity from strong radio sources can hardly exceed 10^{-5} photons cm^{-2} sec^{-1} above 100 MeV; this estimate is based on the

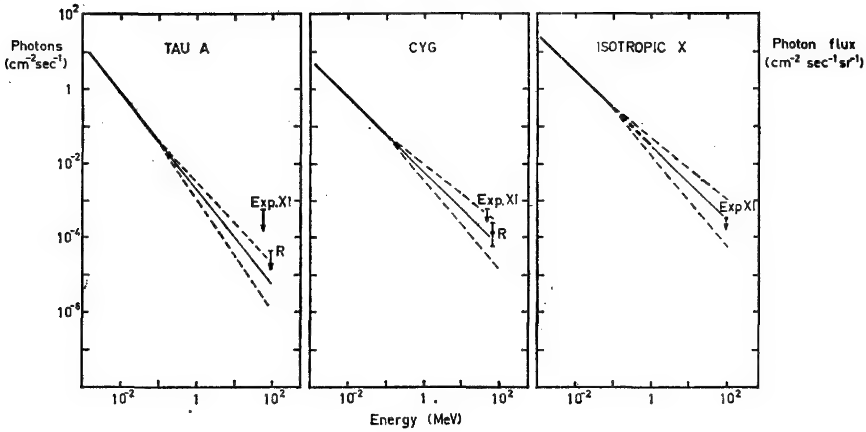

FIG. 5. Extrapolation of X-ray spectra for Tau XR–1, Cyg XR–1 and the isotropic celestial X-rays; the spectra are represented in integral form.

For each spectrum, a thick line represents the observed part; a thin line is the straightforward extrapolation up to 100 MeV. The dotted lines indicate the probable range of uncertainty. The results of the Explorer XI experiment (Kraushaar *et al.* 1965) are marked Exp. XI; those of Rochester experiments (Cobb *et al.* 1965, Duthie *et al.* 1966) are marked R.

hypothesis that pion production by cosmic-ray collisions is the main origin of radio-emitting electrons.

The origin of the *isotropic component* of celestial X-rays is entirely unknown. Felten and Morrison (1963; see also Felten 1965) have proposed X-ray generation in intergalactic space by inverse Compton effect. However, this requires too large a flux of high-energy electrons in intergalactic space. Rather, one may account for the spectrum and intensity of background X-rays by superposition of the X-rays from all external galaxies, provided that the greater part of X-ray sources have a power-law spectrum.

As shown in Figure 5, the extrapolation of the isotropic X-ray spectrum is also in good agreement with the flux of diffuse gamma-rays observed in the Explorer XI experiment (Kraushaar *et al.* 1965), which the authors state to be an upper limit. Further observations are undoubtedly needed to establish a definite flux value.

In particular, improvement of angular resolution is necessary in order to distinguish weaker gamma-ray sources from the background radiation. With present-day techniques we can obtain an angular resolution as good as 3° for gamma-rays of 100 MeV. The smallest source intensity then detectable will be of the order of 10^{-6} photons cm^{-2} sec^{-1}.

Another important aspect of gamma-ray observations is the investigation of *interstellar matter*. If, as appears most probable, neutral-pion production by cosmic-ray interactions is the main source of interstellar gamma-rays, the flux is then proportional to $j_{cr}\,\rho$, where j_{cr} is the cosmic-ray intensity and ρ the density of interstellar matter. Therefore, if we observe these interstellar gamma-rays, we obtain the total density of interstellar matter (not only neutral hydrogen), which is yet undetermined.

The interstellar gamma-rays will show a strong anisotropy, reflecting the distribution of the gas which is highly concentrated to the galactic plane. Therefore, with a detector

of good angular resolution, a sharp peak in the distribution of interstellar gamma-rays should be observable along the galactic equator, even if the background gamma-rays are as intense as suggested by the Explorer XI experiment.

REFERENCES

Bleeker, J. A. M., Burger, J. J., Scheepmaker, A., Swanenburg, B. N., Tanaka, Y. 1966, *Phys. Lett.*, **21**, 301.

Bleeker, J. A. M., Burger, J. J., Deerenberg, A. J. M., Scheepmaker, A., Swanenburg, B. N., Tanaka, Y. 1967, *Astrophys. J.*, **147**, 391.

Bowyer, S., Byram, E. T., Chubb, T. A., Friedman, H. 1964*a*, *Nature*, **201**, 1307.

Bowyer, S., Byram, E. T., Chubb, T. A., Friedman, H. 1964*b*, *Science*, **146**, 912.

Byram, E. T., Chubb, T. A., Friedman, H. 1966, preprint.

Cobb, R., Duthie, J. G., Stewart, J. 1965, *Phys. Rev. Lett.*, **15**, 507.

Duthie, J. G., Cobb, R., Stewart, J. 1966, *Phys. Rev. Lett.*, **17**, 263.

Felten, J. E. 1965, *Phys. Rev. Lett.*, **15**, 1003.

Felten, J. E., Morrison, P. 1963, *Phys. Rev. Lett.*, **10**, 453.

Fisher, P. C., Johnson, H. M., Jordan, W. C., Meyerott, A. J., Acton, L. W. 1966, *Astrophys. J.*, **143**, 203.

Frye, G. M., Smith, L. H. 1966, *Phys. Rev. Lett.*, **17**, 733.

Grader, R. J., Hill, R. W., Seward, F. D., Toor, A. 1966, *Science*, **152**, 1499.

Hayakawa, S. 1966, Internal Report, Nagoya Univ.

Hayakawa, S., Matsuoka, M., Ogawa, H., Yamashita, K. 1966, COSPAR 7th Int. Space Science Symp., Vienna.

Haymes, R. C., Craddock, Jr., W. L. 1966, *J. geophys. Res.*, **71**, 3261.

Kraushaar, W., Clark, G. W., Garmire, G., Helmken, H., Higbie, P., Agogino, M. 1965, *Astrophys. J.*, **141**, 845.

McCracken, K. G. 1966, in *Proceedings Ninth International Conference on Cosmic Rays* (London, September 1965), Ed. A. C. Stickland, Vol. 1, publ. by the Institute of Physics and the Physical Society, London, p. 449.

Metzger, A. E., Anderson, E. C., Van Dilla, M.A., Arnold, J. R. 1964, *Nature*, **204**, 766.

Peterson, L. E., Jacobson, A. S., Pelling, R. M. 1966, *Phys. Rev. Lett.*, **16**, 142.

Rothenflug, R., Rocchia, R., Koch, L. 1966, in *Proceedings Ninth International Conference on Cosmic Rays* (London, September 1965), Ed. A. C. Stickland, Vol. 1, publ. by the Institute of Physics and the Physical Society, London, p. 446.

Discussion

M. P. Savedoff: Frye and Smith (1966) have recently made gamma-ray measurements at 30 to 500 MeV. They report 8 counts attributable to the Crab against a background of 3. Although this does not establish the existence of a gamma-ray source in the Crab Nebula, it provides an excellent estimate of the flux near 50 MeV: 2×10^{-4} photons cm^{-2} sec^{-1}. (The paper by Frye and Smith gives $1{\cdot}9 \times 10^{-4}$ photons cm^{-2} sec^{-1}, as 'upper limit at the 95% confidence level'. —*Editor*.)

I.A.U. Symposium no. 31, 1967

77. THEORETICAL IDEAS CONCERNING X-RAY SOURCES
(Invited Paper)

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ABSTRACT

Several possible mechanisms for the emission of galactic X-ray sources are briefly reviewed. Synchrotron radiation is probably responsible for the X-ray emission from the Crab Nebula and from Cas A. The source Sco X–1 probably radiates by thermal bremsstrahlung in a cloud at 50×10^6 °K, associated with an old nova. The energy source of the hot gas in such a model, and the conditions for formation of the line spectrum are considered.

1. INTRODUCTION

Rossi has given an account (Paper 75) of the present status of observational X-ray astronomy. A considerable number of discrete X-ray sources have been discovered in the last three or four years. In addition, a background flux of X-rays and gamma-rays has been detected. It appears that the latter flux is extragalactic in origin, arising either from X-ray sources in a large number of external galaxies, or by the inverse Compton process in which high-energy electrons are scattered on low-energy photons in the intergalactic medium; I shall not discuss this flux here, since we are restricting this Symposium to the Galaxy. For the same reasons I shall not examine the possible identification of discrete sources with extragalactic objects.

There have been a number of reviews describing the physical mechanisms which may give rise to hard photons in the Universe. Fairly complete analyses have been given by Ginzburg and Syrovatskij (1964), by Hayakawa *et al.* (1966), and by Gould and Burbidge (1967). I shall not treat all of these physical mechanisms, but shall restrict myself to four which have been frequently discussed, namely, black-body radiation, the inverse Compton process, synchrotron radiation, and thermal bremsstrahlung from optically thin gas. I shall consider these mechanisms in relation to the galactic sources only.

2. FOUR MECHANISMS OF X-RAY EMISSION

The idea that a *very hot black body* could be responsible for the X-ray emission from discrete sources was advanced very strongly by Friedman and his associates, together with a number of theoreticians, when the Crab Nebula was first identified as an X-ray source (Bowyer *et al.* 1964). The idea was that the black body was a *neutron star*, which had been formed in the supernova explosion. The objections to this hypothesis are now well known. The source in the Crab has an energy spectrum (cf. Paper 76, Figure 2) which is certainly not that of a black body; the source is known to have a finite angular size, and the rate of cooling of a hot neutron star through neutrino emission is so high that its lifetime at a temperature exceeding 10^6 to 10^7 °K will be extremely short, much shorter than the life of the Crab Nebula. Most people have concluded, therefore, that

neutron stars acting as black bodies probably cannot account for the galactic X-ray sources. However, there are some who still believe that the ultimate energy source which gives rise to X-ray emission is the internal energy contained in neutron stars. It is argued that this energy is transformed ultimately to X-rays through one of the other mechanisms mentioned above.

The *inverse Compton process* requires the existence of regions of high radiation density in which high-energy electrons are present. Such regions would be exceedingly bright at optical frequencies, and the known energy densities of radiation in the regions where discrete X-ray sources are seen are not high enough to give appreciable fluxes of X-rays. Only in the quasi-stellar objects, which are certainly extragalactic, is there the strong possibility that the inverse Compton process is effective.

Thus we are left with *synchrotron radiation* and *thermal bremsstrahlung*. Let us consider these briefly in connection with the X-ray sources in the Galaxy which have been identified with optical objects.

The *Crab Nebula* was the first optical object identified with an X-ray source. Measurements of the X-ray flux have been made in the range 1–100 keV as has been mentioned by Rossi (Paper 75, Section 3*b*) and by Tanaka (Paper 76, Figure 2). It is known that both the radio and the optical emission from this object are due to the synchrotron process. Since the spectrum can, throughout the whole range from radio to X-ray frequencies, be represented by $P(\nu) \propto \nu^{-\alpha}$, with α increasing at the high-frequency end, the synchrotron process may be responsible for the X-ray flux also. This question has been discussed by Burbidge, Gould, and Tucker (1965), by Ginzburg (1966) and by Šklovskij (1966). Tucker (1966) has recently analyzed the possible models in detail. In order to obtain hard radiation by the synchrotron process, one requires high-energy electrons or strong magnetic fields, or both. For example, in a magnetic field of 10^{-4} gauss, electrons with energies of about 5×10^{13} eV are required to radiate photons of 10 keV. Such electrons have half-lives of the order of 25 years. Thus the synchrotron process requires the continuous acceleration or injection of electrons of very high energy. Some workers are still inclined to the view that the bremsstrahlung process is responsible for the hard radiation from the Crab, but it is then necessary to invoke very high temperatures to explain the high-energy tail of the X-ray spectrum; or one must have recourse to non-thermal bremsstrahlung, which leads to other difficulties. At present I think that the synchrotron process is the most natural explanation of the hard photons from the Crab Nebula.

There is now also a tentative identification of a source of X-rays in the 2 to 8 Å region with the radio source *Cassiopeia A*. This is the strongest non-thermal radio source in the sky and is a supernova remnant. Gould has recently informed me that an extrapolation with constant slope of the radio spectrum fits the X-ray flux detected from this source. This may indicate that its X-rays are produced by the synchrotron process, though the lifetimes of the X-ray electrons will be shorter by a factor $\geqslant 10^4$ than those giving rise to the radio emission.

3. THE NATURE OF SCO X-1

The most recent optical identification is that of Sco X-1 with a bright blue, star-like object, as has just been described by Rossi (Paper 75, Section 4). It appears highly probable that the identification is correct. Preliminary determinations of spectrum and

color suggest that the object has the optical characteristics of an ex-nova. It is of some interest to discuss the kind of model which may be constructed from the data at hand. The ideas that I shall describe in what follows arose in a discussion between Rossi, Ginzburg, Šklovskij, Woltjer, and myself, together with some others, which was held in Noordwijk a few days ago.

The X-ray spectrum of Sco X-1 (see Rossi, Paper 75, Section 3*a*, and Tanaka, Paper 76, Figure 1) indicates an exponential law; this is thought to show that it is a *thermal-bremsstrahlung* source, in which case a temperature of about 50×10^6 °K is required. The total power emitted by the source is uncertain because its distance remains unknown*, but we shall, in what follows, assume that the distance is 250 pc and, consequently, the total power emitted is 10^{36} erg/sec. On this basis, and adopting a temperature of 50×10^6 °K in a uniform cloud, we can easily compute the dimensions of the cloud, its energy content, and its cooling time (energy content divided by total power), as a function of the electron density, n_e. Results are given in Table 1. Since the X-ray source is known to have an angular size $<20''$, the dimension R must be less than 8×10^{16} cm. If we suppose that the hot gas cloud also gives rise to the optical object, an assumption which was made as one of the steps leading to the optical identification, then since it is star-like we must take an angular size $< 1''$, or $R < 4 \times 10^{15}$ cm.

Sandage *et al.* (1966) have pointed out that the spectrum of the optical object is reminiscent of that of an *old nova*. While it is possible to argue that the object is a new type of astronomical object, and that the similarity of spectral characteristics is only superficial, we shall in the following discussion make the natural assumption that the object is indeed an old nova.

Table 1

Properties of uniform clouds with $T = 50 \times 10^6$ °K required to give X-ray flux from Sco X-1

n_e (cm^{-3})	R (cm)	Energy content, E (erg)	Cooling time (sec)
$10^{4.5}$	3×10^{16}	2×10^{46}	2×10^{10}
10^{6}	3×10^{15}	6×10^{44}	6×10^{8}
$10^{7.5}$	3×10^{14}	2×10^{43}	2×10^{7}
10^{9}	3×10^{13}	6×10^{41}	6×10^{5}
$10^{10.5}$	3×10^{12}	2×10^{40}	2×10^{4}
10^{12}	3×10^{11}	6×10^{38}	600
$10^{13.5}$	3×10^{10}	2×10^{37}	20
10^{15}	3×10^{9}	6×10^{35}	0·6

* At the time of this talk we were not familiar with the work of Friedman, who has argued from his detection of a flux of much softer X-rays that the object must be comparatively nearby, since if it were at a distance exceeding 100 pc, the absorption of these X-rays by the interstellar gas would be very large. This point remains unclear at the time of writing. It has been realized that it is possible to obtain a direct estimate of the amount of interstellar matter lying between Sco X-1 and the solar system, independently of the distance assumed for the source, from the strength of the interstellar Ca^+ lines in the optical spectrum. This rough estimate suggests that $\tau \geqslant 5$ for the soft X-rays. Thus the difficulty is severe. Possible ways out are (*a*) that an immense flux of soft X-rays is generated by this source, much larger than that generated by a 50×10^6 °K plasma, (*b*) that the observation of soft X-rays associated with Sco X-1 is spurious, (*c*) that the optical identification is incorrect.

It has been known for some years that a number of ex-novae are ***close binary*** systems. Kraft has given plausible arguments for supposing that the nova phenomenon is closely tied to the binary nature of the system, and that all old novae are binaries. In the systems which have been studied in detail it has been shown that the two stars are exceedingly close together and are moving with relative velocities of some 500 km/sec. The periods are very short, of the order of hours in some cases. One of the stars is a highly evolved object which contributes little to the optical luminosity. In order to explain the X-ray properties of such an object we have to consider two questions:

(*a*) What is the source of the energy for the hot cloud, and in what way is it related to the binary system?

(*b*) Where does the line spectrum originate?

(*a*) *Energy source*

We were naturally led first to the idea that the hot gas cloud forms a ***hot corona*** about the binary system. An attractive possibility here is that this gas cloud is gravitationally contained by the binary, and that its energy source is the ***gravitational potential energy of the system***. Thus we must suppose that the gas cloud has dimensions no greater than the separation between the stars, i.e. about 10^{11} cm, so that $n_e \approx 10^{13}$ cm^{-3}; if the gas occupied a larger volume it would escape. The mechanism of heating in this model is the stirring of the corona by the stars moving in it, and the maximum temperatures that can be generated are given approximately by $T \approx m_p v^2/k \approx 25 \times 10^6$ °K for $v \approx 500$ km/sec. The snag associated with this mechanism was pointed out by Prendergast. It is simply that such a heating process may be effective only as long as the corona is practically at rest; if the corona begins to co-rotate with the stars, it will no longer work. One alternative possibility then, suggested by Ginzburg, is that the energy is derived from a *stellar wind*—gas must be ejected from one or both of the stars at velocities of the order of 10^3 km/sec. It is important to realize that these two suggestions concerning the mechanism of the heating of the gas involve two quite different energy sources. In the first case we are utilizing the gravitational energy of the binary system. In the second we must derive the energy from the ***internal energy of one or the other of the stars***. Conventional thermo-nuclear or gravitational energy sources might be invoked. Alternatively one might suppose that the highly evolved component of the binary system is a neutron star, and that the internal energy of this star is being slowly released in the form of high-velocity gas.

(*b*) *Origin of the line spectrum*

Finally, we must consider the problem where the optical line spectrum originates. The observed emission lines include the Balmer lines, He II λ4686, and high-excitation lines due to C^{++}, N^{++}, and O^{+}. Such lines are produced in stellar atmospheres with temperatures of 25 000 to 50 000 °K, and while this is very hot for a stellar atmosphere, it is a very cool region as compared with the plasma giving rise to the X-ray flux. It is therefore necessary to consider ways in which such a cool region can exist in conjunction with an exceedingly hot plasma. This problem has not been solved, though it is clear that, since the hard radiation emitted by the hot plasma will ionize the outer atmospheres of both stars, we must suppose that the line formation takes place in conditions of high density, where the ionizing effect is significantly reduced. Very severe limits are probably placed on the model by this condition.

(c) *Frequencies of novae and of X-ray sources*

Novae explode in our Galaxy at the rate of about 30 per year; after the explosion they still contain appreciable energy sources—many are recurrent—and they remain optically detectable. Thus many millions of ex-novae should be present in our Galaxy. However, it is clear that only a small fraction of these are emitting significant fluxes of X-rays. It may very well be that the majority of the known X-ray sources are ex-novae, though present evidence shows that some supernova remnants are also emitting X-rays. Why should only a small fraction of the ex-novae be X-ray sources? On the basis of the ideas developed here there are many possible explanations. It may be that only in rare cases, or for a short time, is it possible for gas to be heated by the two stars. Alternatively it might be supposed that only in a few cases is the gas heated to temperatures in excess of 10^7 °K, while in most ex-novae the gas is cooler and fluxes of much softer X-rays are emitted.

These ideas have been developed very hurriedly following the optical identification of Sco X–1. Much more work is required to produce a detailed model, and it may be found that some of the views expressed will not survive detailed investigation.

REFERENCES

Bowyer, S., Byram, E. T., Chubb, T. A., Friedman, H. 1964, *Nature*, **201**, 1307.
Burbidge, G. R., Gould, R. J., Tucker, W. H. 1965, *Phys. Rev. Lett.*, **14**, 289.
Ginzburg, V. L. 1966, *Astr. Zu.*, **43**, 897 (translation in: 1967, *Soviet Astr.*, **10**, 719).
Ginzburg, V. L., Syrovatskij, S. I. 1964, *The Origin of Cosmic Rays*, Pergamon Press, Oxford.
Gould, R. J., Burbidge, G. R. 1967, *Handbuch der Physik*, Vol. 46/2, Springer Verlag, Berlin/Göttingen/Heidelberg, p. 265.
Hayakawa, S., Matsuoka, M., Sugimoto, D. 1966, *Space Sci. Rev.*, **5**, 109.
Sandage, A. R., Osmer, P., Giacconi, R., Gorenstein, P., Gursky, H., Waters, J. R., Bradt, H., Garmire, G., Sreekantan, B. V., Oda, M., Osawa, K., Jugaku, J. 1966, *Astrophys. J.*, **146**, 316.
Šklovskij, I. S. 1966, *Astr. Zu.*, **43**, 10 (translation in 1966, *Soviet Astr.*, **10**, 6).
Tucker, W. H. 1966, Thesis, University of California at San Diego, to be published.

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78. ON THE POSSIBLE GAMMA-RAY SOURCE IN CYGNUS

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ABSTRACT

A source of gamma rays has been found at right ascension $20^h\ 15^m$, declination $+35°$, with an uncertainty of 6° in each coordinate. Its flux is $(1{\cdot}5 \pm 0{\cdot}8) \times 10^{-4}$ photons cm^{-2} sec^{-1} at 100 MeV. Possible identifications are reviewed, but no conclusion is reached. The mechanism producing the radiation is also uncertain.

1. OBSERVATIONS AND ANALYSIS

Evidence has been found (Duthie *et al.* 1966) for a source of gamma rays in the constellation Cygnus. The flux received is $(1{\cdot}5 \pm 0{\cdot}8) \times 10^{-4}$ photons cm^{-2} sec^{-1} at 100 MeV. The direction of the source is $\alpha = 20^h\ 15^m$, $\delta = +35°$, with an uncertainty of 6° in each coordinate.

The detector used to find this source was a spark chamber triggered by a counter telescope. The observational result was obtained by examining photographs of tracks recorded in the spark chamber during exposure of the detector at an altitude of 120 000 feet (36 km), corresponding to a residual atmosphere of 4 g/cm². This is small compared to the interaction length in the atmosphere of protons (90 g/cm²) and gamma rays (37·7 g/cm²). A lead plate converted the gamma rays into electron-positron pairs.

In the observations there are two anomalies which we interpret as evidence of a source of gamma radiation. First the bisectors of the positron and electron directions were obtained. These bisector directions were then assembled into cells of equal size and exposure. The cells were all 9° wide in right ascension and 30° wide in declination, and were all centered at declination $+31{\overset{\circ}{.}}5$, the approximate zenith throughout the flight of the detector. The mean number of events per cell was 19·5; at 20^h right ascension the number was 31·8. The fractional counts are a result of statistical removal of background fluctuations expected from slight altitude variations throughout the flight. The size of the cells may appear large, but it reflects the crudeness of the directional information as we shall show presently. The count in the cell at 20^h right ascension represents an excess of 2·8 standard deviations, an occurrence which should appear once per 300 cells, while we have 16 cells in our sample. The excess count is interesting, but by itself it is not statistically very convincing. What is significant, however, is that a second parameter is anomalous in the same part of the sky.

The opening-angle distribution of detected events over the whole sky has a broad maximum extending over ten degrees. The breadth of this distribution indicated that the present experimental device is not good for the angular resolution of sources. The angular uncertainty in the direction of any photon is of the order $\theta/2$, where θ is the opening angle of the pair.

Examination of our data concerning the rate anomaly in the region of $\alpha = 20^h$ suggested that the anomaly might be centered at about $\delta = +35°$. We selected all events whose bisector fell within a box, 18° by 18° in size, centered at $\delta = +35°$, $\alpha = 20^h$. A statistical analysis of the opening-angle distribution of these events indicated that it was not consistent with the distribution over the whole sky discussed in the previous paragraph. A χ^2 test of the hypothesis that this distribution could have arisen as a result of statistical fluctuations indicated that there was only one chance in 300 of such an occurrence.

From an analysis of scans at fixed declinations, we estimate the location of the source at $\alpha = 20^h\,15^m$, $\delta = +35°$. The distribution of events around this location has a halfwidth of 12°.

Other experimenters have exposed detectors to look for primary gamma-rays. In the same region, Kraushaar *et al.* (1965) with the Explorer XI experiment set an upper limit of 5×10^{-4} cm^{-2} sec^{-1} on the flux of Cyg A at 100 MeV, and Frye and Smith (1966) have set upper limits of $1{\cdot}8 \times 10^{-4}$ cm^{-2} sec^{-1} on both Cyg XR–1 and Cyg A. Neither of these results is inconsistent with our own observations of a flux of $1{\cdot}5 \times 10^{-4}$ cm^{-2} sec^{-1}.

2. POSSIBLE IDENTIFICATIONS

For purposes of identification, we consider the region from $19^h\,9^m$ to $20^h\,54^m$ in right ascension and from +23° to +47° in declination as having a high probability of including the source. The history of attempts to identify radio sources in 1948, when similar directional information was available, warns us against too great optimism.

This region, for example, contains four stars brighter than magnitude 3: δ Cyg, γ Cyg, α Cyg and ϵ Cyg. It further contains the nova of 1670 (CK Vul) as well as the shell star P Cyg. One can choose between six planetary nebulae and twenty-six H II regions out of Sharpless's list of 313. It is unlikely that any of these common objects is uniquely bright in the gamma-ray region.

The revised 3C catalogue lists twelve radio sources in this region, of which Cyg A (3C 405) is a well-known suspected gamma-ray and X-ray source. At 178 MHz, it is approximately twenty times brighter than the brightest parts of Cyg X, which is believed to be a collection of H II regions.

Among the observed X-ray sources reported by Friedman's group at the Naval Research Laboratory, Cyg XR–1 and Cyg A are within this region. To our knowledge, only Tau XR–1 has been definitely identified with an optical object, the Crab Nebula.*

Grader *et al.* (1966), of the Lawrence Radiation Laboratory, report that the spectrum of Cyg XR–1 extends further toward high energies than those of Sco X–1 and Tau XR–1. At energies above 100 keV, it appears to be the brightest X-ray source known. Cyg XR–1 is also unique among X-ray sources in that Byram *et al.* (1966) report a 75% decrease of its intensity in 10 months—cf. Paper 75, Section 2.

3. POSSIBLE EXPLANATIONS

With our present scanty knowledge of this source, it is difficult to be precise in explaining the origin of the radiation. The following statements, however, appear reasonably supported.

* See, however, the report by Rossi (Paper 75).—*Editor.*

(*a*) The radiation is not produced in the same way as the background X-rays (that is, as a decay product of π-meson production from interactions of cosmic rays with local gas). If this were the case, the opening-angle distribution would be much narrower.

(*b*) The radiation could be produced by proton-antiproton annihilation, although we have not quantitatively examined this unlikely possibility yet.

(*c*) The synchrotron mechanism leads to rather fantastic numbers. For a source at 1 kpc distance, with $H = 10^{-5}$ gauss, one needs 10^{39} electrons with energies of 10^{16} eV or higher and a mean life of 2 months. The X-ray flux from Cyg XR–1 is also unlikely to arise from this mechanism, for the same reason.

(*d*) Bremsstrahlung seems the most likely process. It would require electrons of energies comparable to those observed in the local cosmic rays (say above 10^8 eV) in numbers like 3×10^{55} for a source of 1 kpc distance, and density 1 hydrogen atom/cm^3. For condensed matter, say 10^{12} atoms/cm^3, the energy remains the same but only 3×10^{43} electrons would be required. The lifetime of those electrons would be 10^9 years for interstellar densities, and 10 hours for densities of 10^{12} cm^{-3}.

(*e*) The inverse Compton effect could scatter some of the observed X-rays into our measuring band. Because of the small cross-section, bremsstrahlung would exceed the inverse-Compton radiation by the same electrons for densities above 10^{-5} cm^{-3}. The optical photon spectrum is unknown. For 1-eV photons scattered by electrons of 5×10^9 eV to produce the observed flux, about 10^{54} electrons would be required, if one assumes a photon density of 1 cm^{-3}, characteristic of the Galaxy, and a distance of 1 kpc.

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REFERENCES

Byram, E. T., Chubb, T. A., Friedman, H. 1966, *Science*, **152**, 66.
Duthie, J. G., Cobb, R., Stewart, J. 1966, *Phys. Rev. Lett.*, **17**, 263.
Frye, G. M., Smith, L. H. 1966, *Phys. Rev. Lett.*, **17**, 733.
Grader, R. J., Hill, R. W., Seward, F. D., Toor, A. 1966, *Science*, **152**, 1499.
Kraushaar, W., Clark, G. W., Garmire, G., Helmken, H., Higbie, P., Agogino, M. 1965, *Astrophys, J.*, **141**, 845.

NOTE ADDED TO PROOF

In a paper published after the submission of this report, Frye and Wang (1967) claim that they have found no evidence to support our observation. We have re-evaluated our data and found no evidence of instrumental malfunction. Suggestions of large time variations in the intensities of X-ray sources in this region have been made by Friedman *et al.* (1967). Such effects may also explain the inconsistencies between our own and Frye's data.

Frye, G. M., Wang, C. P. 1967, *Phys. Rev. Lett.*, **18**, 132.
Friedman, H., Byram, E. T., Chubb, T. A. 1967, *Science*, **156**, 374.

79. DISCUSSION ON X-RAY SOURCES

K. Takakubo: I show a reproduction of the two-colour plate of the region around Sco X–1 mentioned by Rossi (Paper 75, Section 4*d*). The plate was taken by M. Oda, K. Ichikawa, G. Ishida, J. Jugaku, K. Osawa, and M. Shimizu with the 74-inch (188-cm) reflector at Okayama Observatory on 17 June 1966. Two exposures were made on this plate, through *U* and *B* filters. It displays a very blue object of magnitude 12·5, very near the position of Sco X–1 determined recently.

G. H. Herbig: It is apparent that the spectrum of the star observed by Sandage *et al.* (1966, Figure 4) at the position of Sco X–1 is not that of some hitherto unknown type of object, as they recognize, but that of a variety of hot variable star of which roughly a dozen examples are known. Probably these stars are not at all rare objects per unit volume, in comparison to more familiar kinds of high-luminosity variables. Spectra such as these, with emission lines of H and He II and weaker lines of ions of C, N, and O, are characteristic of the irregular eruptive variables near minimum light. These objects also have the rapid 'flickering' in light, with a time-scale of minutes, and the slower hour-to-hour rise and fall that are observed in the Scorpius object. Among these variables one finds very active objects having no known eruptions (like BD + 14° 342 and UX UMa), together with the SS Cyg or U Gem variables, the recurrent novae (like WZ Sge, which last was bright only 20 years ago), and the ordinary novae. A group characteristic seems to be that they are close binaries with periods between $1\frac{1}{2}$ and 6 to 8 hours, and orbital velocities of several hundred km/sec, and the photometric activity may well be connected with the binary nature.

It is urgent that, if the Scorpius X-ray source is to be identified with this star, other members of the family should be examined for X-radiation. If no other coincidences are found, then some explanation is in order. One notes that one of the Cygnus sources lies not far from the well-known bright eruptive variable SS Cyg; but, clearly, better X-ray positions are needed before we can take such things entirely seriously.

I might note that the interstellar Ca II lines in the star observed by Sandage *et al.* seem to me to be surprisingly strong, as judged from reproductions of 85 Å/mm spectrograms, for an object in this part of the sky and at a distance of about 200 pc.

L. Biermann: I have a question to Burbidge's team, who apparently have thought about this model of Sco X–1 (Paper 77, Section 3). Is it obvious that one has to rely on the kinetic energy of relative motion of the two components of the system? Could it not be that the binary nature itself triggers instabilities of some kind?

G. R. Burbidge answers: Yes, possibly.

V. L. Ginzburg: The model of a binary system for Sco X–1 seems to me very attractive. As noted by Herbig, the potential and kinetic energy of the double system is of the order of 10^{49} erg. This is an enormous amount, and we must find ways to use it for maintaining the X-ray emission. (In fact, the nova explosion itself may be the result of some instability in a close binary system.) Tidal effects may produce streams of matter or stellar winds, and these may hit the surface of a star or produce a transient atmosphere. The mass

loss involved would be rather low, 10^{18} or 10^{20} g/sec. Such values are well within the range of possibilities.

The fact that the number of bright X-ray sources is small in comparison with that of novae exploded in the last 100 or 1000 years, does not present a real problem. This becomes clear from the following argument. The power L of a bremsstrahlung emitter is proportional to $n^2\ V\ T^{1/2}$, where n is electron density, V volume and T temperature. If X-ray sources emit bremsstrahlung, a change of L_X by 1 or 2 orders of magnitude, which could make a source undetectable, appears quite natural. Furthermore, since the spectrum at these frequencies varies as exp $(-h\nu/kT)$, a diminution of the temperature by a factor 2 or 3 will suffice for a sharp decrease of the X-ray emission in the region 1 to 10Å. In the region of $\lambda > 10$Å there are very few measurements, and interstellar absorption can play an important role.

L. Woltjer: I should like to add a column of numbers to Burbidge's Table 1 (Paper 77). The expansion time scale, R divided by 3×10^7 cm/sec, is 10^9, 10^8, 10^7 sec and so on. Even on the most favourable assumptions, the possibility of magnetic confinement or of gravitational confinement arises only for the smaller sizes, with radii below 10^{14} cm.

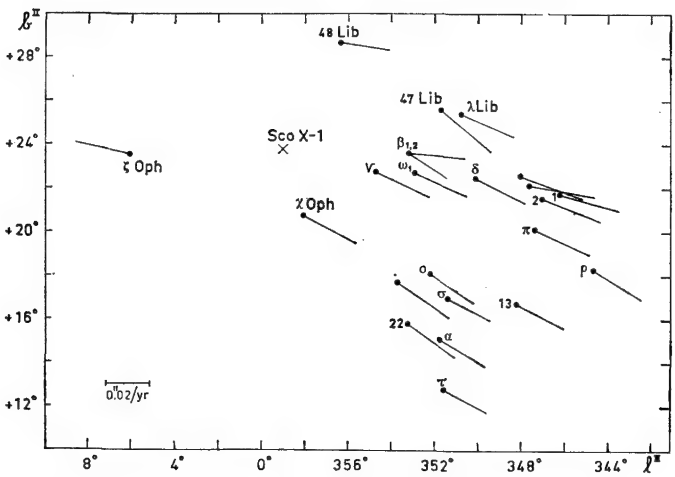

FIG. 1. The position of Sco X-1 with respect to the bright members of the Sco II association and the run-away star ζ Oph. The scale of the proper motions which have been drawn in is at lower left.

A. Blaauw: With reference to the identification of Sco X-1, L. L. E. Braes and I wish to suggest that this source is the stellar remnant of a type-II supernova which exploded about 500 000 years ago in the Sco II association, whose distance is 170 pc. We base this suggestion on the following facts:

(*a*) The position of Sco X-1 on the sky lies in the immediate surroundings of the Sco II association, and between it and the run-away star ζ Ophiuchi (Figure 1). This fact has already been noticed by Braes and Hovenier (1966), in their article on the relation between X-ray sources and supernova phenomena in OB associations.

(*b*) Sco X–1 is similar in colour to the star X Per in the association Per II; moreover both are underluminous irregular variables, and occur in a region of recent star formation.

(*c*) X Per is suspected of being the remnant of the supernova that gave rise to the birth of the run-away star ξ Per (Blaauw 1961).

A reasoning of similarity then leads us to the suggestion that Sco X–1 might be the remnant of the supernova that gave rise to the birth of the run-away star ζ Ophiuchi. The suggested time of 500 000 years is based on the latter's orbit with respect to the region of origin.

G. H. Herbig comments: I do not believe that X Per is an object of the type found in Scorpius by Sandage *et al.* (1966). It rather seems to be an early B-type star with very fast axial rotation, and hydrogen emission lines of the ordinary Be variety; the absolute magnitude is perhaps -2 or so. I think there is no evidence either of rapid 'flickering' in the light of X Per, of the kind that is found in the sub-luminous eruptive variables. This does not mean that X Per cannot be the remains of a supernova, or almost anything else one would like, but only that it is certainly quite a different type of hot variable from the ones I discussed above.

Burbidge: What is the radial velocity?

Herbig answers: You can't tell. It's an almost flat, wide-lined spectrum, simply because $v \sin i$ is 400 or 500 km/sec. It looks like the spectrum of an electric light bulb.

C. H. Costain: A preliminary examination of the position of Sco X–1 was made with the 150-foot (46-m) Algonquin Park telescope of the National Research Council of Canada at a wavelength of 2·8 cm. The upper limit obtained for the flux density from this source is $0{\cdot}3 \times 10^{-26}$ W m^{-2} Hz^{-1}.

B. F. Burke: With the 120-foot (37-cm) Haystack antenna of Massachusetts Institute of Technology and Lincoln Laboratory, we have determined an upper limit of $0{\cdot}5 \times 10^{-26}$ W m^{-2} Hz^{-1} on the flux of Sco X–1 at 18 cm wavelength.

K. Takakubo: There is a cluster of X-ray sources in the Cygnus region, where we look through the Orion Arm parallel to its axis. This clustering may indicate that X-ray sources are concentrated in spiral arms.

If one excludes extragalactic sources, supernova remnants, and the sources around the galactic centre, the average X-ray luminosity of the remaining sources is of the order of 10^{35} erg/sec, between 2 and 8 Å wavelength, for an average distance of 500 pc. This average distance is assumed on the basis of the observed clustering in Cygnus. If Sco X–1 has the same X-ray luminosity of 10^{35} erg/sec, it should be at a distance of 100 pc. This is consistent with the small thickness of the Orion Arm in this direction, and with the high latitude of the source.

Probably there are at least three kinds of galactic X-ray sources, as summarized in Table 1.

V. L. Ginzburg: The identification of the radio galaxies Cyg A and Vir A with sources of X-rays (Paper 75, Section 1) requires confirmation, of course. But if this identification is correct, precisely this X-ray emission of the radio galaxies seems to me the most important result of X-ray astronomy. It suffices to note that the X-ray luminosity of

Table 1

Three types of galactic X-ray sources

Type	Representative distance r (kpc)	Luminosity L_X (erg/sec)
Sources around galactic centre	8	5×10^{37}
Supernova remnants		10^{36}
Nearby sources, (including Sco X-1)	0·5 (0·1)	10^{35}

Cyg A would amount to 3×10^{46} erg/sec. This value is two orders of magnitude higher than the radio and optical luminosities.

For the mechanism of X-ray emission by radio galaxies I see only two possibilities (Ginzburg 1966, 1967). One is thermal radiation by large clouds (10^9 solar masses?) of hot gas (50×10^6 °K). This possibility can be proved in principle by optical methods, by measurement of the dimensions of the X-ray source, by observing X-ray lines, etc. The other possibility is an 'X-ray quasar', a very small and powerful X-ray source. In this case particularly we may expect also to receive very short radio waves from the same region. Since X-ray measurements suffer from poor resolution, radio observations at centimeter and millimeter wavelengths would be of great importance. The high-resolution map of Cyg A shown by D. S. Heeschen (Figure 2) is a good example.

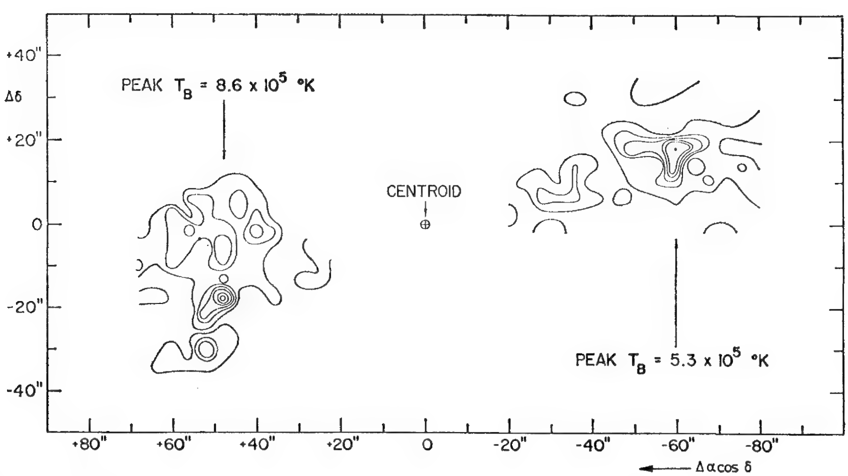

FIG. 2. Brightness distribution in Cygnus A to 11·1 cm wavelength. The observation were obtained at the National Radio Astronomy Observatory, Green Bank, West Virginia U.S.A. Faintest contour: $T_b = 10^{4·5}$ °K; contour interval: $\Delta \log T_b = 0·25$. (Wade 1966)

REFERENCES

Blaauw, A. 1961, *Bull. astr. Inst. Netherl.*, **15**, 265.
Braes, L. L. E., Hovenier, J. W. 1966, *Nature*, **209**, 360.
Ginzburg, V. L. 1966, *Astr. Zu.*, **43**, 897 (translation in: 1967, *Soviet Astr.*, **10**, 719).
Ginzburg, V. L. 1967, IAU Symposium, no. 29, *Instability Phenomena in Galaxies*, in press.
Sandage, A. R., Osmer, P., Giacconi, R., Gorenstein, P., Gursky, H., Waters, J., Bradt, H., Garmire, G., Sreekantan, B. V., Oda, M., Osawa, K., Jugaku, J. 1966, *Astrophys. J.*, **146**, 316.
Wade, C. M. 1966, *Phys. Rev. Lett.*, **17**, 1061.

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Chapter III F

Concluding Remarks

CHAIRMAN: L. Biermann
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> '*These galactic spurs seem to be really exceedingly important things, that tell us something rather significant about the galactic magnetic field, but at the moment it is not quite clear what it is that they tell us.*'
>
> L. Woltjer, in Paper 80

80. REMARKS ON THE GALACTIC MAGNETIC FIELD*

(Concluding Review)

L. WOLTJER

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According to the program I am to speak on the theory of the galactic magnetic field and to summarize. About the theory of the magnetic field I can be very short because no coherent theory exists. In our present state of knowledge one is not even sure what should be expected of the theory. To summarize summarizing papers is probably not too fruitful; I therefore will restrict myself to making a number of somewhat loosely connected remarks on the galactic magnetic field and on some of the observations that might be useful in elucidating the situation.

The basic problem in studies of the galactic magnetic field is that the field, or at least the large-scale field, is intrinsically a non-local property of the Galaxy. In many of the models that are made, field lines are coming out of various sides of the model, but their further path is not traced. In the end, however, one has to consider how to connect things, and that is where the difficulty arises, especially in a system in differential rotation like the Galaxy.

* Supported in part by AFOSR 49(638) 1358.

I. THE LARGE-SCALE FIELD

It seems to me that the most concrete information about the large-scale magnetic field in the Galaxy at present comes from the low-latitude observations of the *Faraday effect* that were discussed yesterday by Davies (Paper 67). The Faraday effect gives the flux-carrying component of the magnetic field. Observations indicate that such a component actually exists. If we knew the electron density along the path that the radiation has traversed, we could estimate the magnitude of this field. Davies arrives at a magnitude of the order of 5×10^{-6} gauss, which seems most representative of the available data, but the result is very uncertain because the electron density is poorly known. A much more accurate measurement of the *electron density* would be of very great value. One can try to measure it by observing the absorption of the radiation of radio sources at low frequencies, but difficulties connected with absorption inside the sources, self-absorption and other things, interfere. It seems important that the determination of the electron density be carried out also by optical methods.

Parenthetically I might remark that the fact that large-scale Faraday effects in the galactic disk are observed, would seem difficult to reconcile with the idea that there is a very patchy *distribution of matter and antimatter*, as suggested this morning by Alfvén (Paper 74, Section 3). Matter and antimatter would give Faraday rotations of opposite sign; a patchy distribution therefore would tend to cancel out any large-scale effects. I think that the observations of Faraday rotation indicate that the scale over which there is one kind of matter cannot be much less than a kiloparsec.

If one tries to assess what the implications are of the large-scale magnetic field revealed by the Faraday effect, then one has to make a choice of two possibilities. One can either assume that the large-scale field in the disk is not wound up by differential galactic rotation, or one can assume that it is.

(a) *The field does not wind up*

If the galactic magnetic field does not wind up, and if it is not much stronger than we think it is, I see no alternative to the conclusion that the main body of the gas is entirely disconnected from the large-scale field, and that this field is embedded in a tenuous background gas that does not rotate with much shear; this picture leads to a number of difficulties. If a field parallel to the galactic plane were strong enough to resist the tendency of the gas to rotate differentially, it could not be confined in the z-direction—i.e., the direction perpendicular to the galactic plane—, because the galactic gravitational force in that direction is too weak. Therefore one would have to make the magnetic field rather complicated so it becomes force-free in the z-direction. This effectively means that there must be a *helical field*. I do not necessarily mean a true helical field as has been postulated in some of the models presented here; an arrangement of field lines winding in random directions around the spiral arms would suffice. In fact, if we think about the origin of the field, it seems exceedingly difficult to visualize how a real topological helix could arise. I said already that a model of the kind discussed implies that the main body of the interstellar gas is disconnected from the large-scale field, and I find it difficult to see how such a state of affairs could persist for a long time, but in the absence of a concrete theory for the dissipative processes in H I regions it is perhaps still premature to draw any very definite conclusions.

(*b*) *The field winds up*

The alternative possibility is that the field winds up. In this case one would expect that the field is mainly in the azimuthal direction. The Faraday observations at low galactic latitudes as plotted by Davies (Paper 67) are in fact consistent with this.* If the field is of the order of 10^{-5} gauss, then with the new values for the layer thickness of the gas suggested by Van Woerden (1967; see also Paper 23), there is no serious problem with the z-distribution of matter and field. It would be valuable if more accurate determinations of the layer thickness and of the z-velocity dispersion of the interstellar gas could be made to strengthen this conclusion.

Now if the magnetic field is well coupled to the gas, then where the gas density is high, the field should be strong. And hence, if we think of the interpretation of spiral structure in terms of density waves (cf. the reports by Prendergast and Lin, Papers 51 and 52), we should expect that the magnetic field would be *concentrated in the spiral arms*. In fact Baldwin, I think, presented some evidence in favor of this conclusion yesterday (Paper 56). Also the fact that the gas, on entering a spiral arm, is compressed mainly in the direction transverse to the arm, leads us to expect the magnetic lines of force to be mostly *parallel to the arm*. This would apply not only to large-scale fields. If a gas having a small-scale field with completely random distribution of field lines entered the spiral arm, one would expect, because the compression of the gas is essentially one-dimensional, that a distribution would be created which would favor directions parallel to the arm. Thus the observation that both the polarization of the synchrotron radiation and the polarization at optical wavelengths indicate magnetic fields which are parallel to the galactic plane and probably also parallel to the spiral arms, is not unexpected and has no direct bearing on the scale of the field. This point was already emphasized by Spitzer and Tukey (1951) fifteen years ago. If the anisotropic compression of matter in a spiral arm is the cause of the field distribution, this implies that the interstellar gas clouds containing the magnetic field would have to be anisotropic. It would be very interesting if observations showed that interstellar clouds are not spherical but rather *elongated structures*, but this may remain very difficult as long as the 21-cm observers cannot even agree that they see clouds at all (cf. Paper 23). Of course it is not so surprising that we see some evidence of cloudy structure in the optical absorption lines and not much in the 21-cm line, because the optical absorption lines give us information about the distribution of the square of the density, while the 21-cm emission gives us information about the density to the first power.

(*i*) *The field at low galactic latitudes*

If we now take an exceedingly simple picture of this winding-up, some trouble arises. Let us suppose, for example, that originally there was a uniform magnetic field in the galactic plane. If, as a result of differential rotation, this magnetic field has been wound up, we should expect that by now the number of windings would be very large. In the region between 7 and 13 kpc distance from the center, roughly every five hundred million years one winding would be added, and so after 10^{10} years we would have a field going around twenty times. The field direction would change sign twenty times over this distance interval, or about every few hundred parsecs. This hardly seems compatible with the Faraday observations. We can remedy the situation to a certain extent by

* A very recent discussion by Berge and Seielstad (1967) indicates that the actual situation may be more complex than would appear from the discussion by Davies.

making more complicated models, for example, by beginning with magnetic fields that are inclined to the plane of the Galaxy. But I think the argument indicates the importance of a much more extensive *survey for polarization and Faraday rotation* in sources at very low galactic latitudes. This appears to be our only chance to obtain information on the sense of the magnetic field in spiral arms other than our own.

Returning for a moment to the flux-carrying component of the magnetic field, we inquire about its *origin*. By making the usual calculations for a magnetic field on a galactic scale, we easily find that common resistivity would give a very long lifetime for the field, 10^{30} years or something like that. We know of course that other dissipative processes may be of importance, but I do not think that a plausible alternative has been given to the conclusion that the large-scale flux-carrying component of the field must be *primeval*, that is, present already in the matter from which our Galaxy condensed.

(*ii*) *The field at higher latitudes*

Next we consider the magnetic fields at somewhat higher latitudes above and below the galactic equator. The observational situation here still seems to be confused. Some have tried to interpret the Faraday data in terms of helical magnetic fields that have been subject to a strong shear; others have pointed out that perhaps these are really rather local fields. Concerning the origin of the magnetic fields at intermediate and higher latitudes, two different kinds of suggestions have been made.

Hoyle and Ireland (1961) have proposed that, if the magnetic field is winding up, it might be subject to the same *instability* as a tightly wound elastic string: from time to time a winding might be lost in the z-direction. It is somewhat doubtful that the field in our Galaxy is wound so tightly that this would really happen. Setti (1965) has made a stability calculation of a certain class of models relating to this situation and found that the galactic gravitational field in the z-direction is strong enough to provide at least linear stability.

The other kind of instabilities, discussed by Pikel'ner and more recently by Parker (1965), are caused by the *cosmic-ray gas*. These are Rayleigh-Taylor-type instabilities that arise because the high-pressure, low-density cosmic-ray gas is kept under a lid of dense, low-pressure matter. In these instabilities the gas falls down while the cosmic rays rise up in a kind of bubble. Such instabilities may occur if the energy density of the cosmic rays decreases with increasing distance from the galactic plane. At present I think it certainly is likely that these instabilities may sometimes occur, but I am not sure how frequently, and what effect they may have. Of course we shall also have to incorporate in these considerations the observations of *high-velocity clouds* that have been discussed by Blaauw (Paper 45) and Oort (Paper 46), because the whole stability situation changes in a rather fundamental way if there is a steady downward stream of matter. I have some difficulty seeing to what kind of final steady state these Rayleigh-Taylor-type instabilities would lead. It is easy to see how the instability would arise and grow, but not how the original situation could in any sense be restored. If these bubbles remain, then one might wonder whether the galactic disk would not be perforated too much, so that the cosmic rays would stream out more or less freely.

It is also not clear in how far instabilities of this kind can account for the *spurs* in the galactic continuum radiation. If we identify the spurs with the cosmic-ray bubbles, the latter should be rather rare. If not, then the observed spurs would probably be quite

near to us and the integrated brightness of all such objects would become larger than what is actually observed.

The spurs bring us to the question of the existence of the *radio halo*. This is basically an observational question; the doubt about it is mainly due to the uncertainty of the background contribution to the observed radiation at high latitudes. As I understand it, the reasoning used by Baldwin (Paper 56, Sections 4 and 5*b*) to establish the background depended on the variation with intensity of the spectral index for the high-latitude radiation. Of course such a correlation would be expected if a constant background is superimposed on a galactic contribution of varying intensity and different spectrum: where the intensity is weak, one expects to see mainly the background radiation, and if this radiation has a steeper spectrum it fits the observed situation that low intensity correlates with large spectral index. On the other hand, this correlation may also arise for galactic radiation, if the energy spectrum of the electrons is curved such that it steepens toward greater energies. For at a fixed frequency a weaker field corresponds to particles of greater energy; and on the average weak fields tend to lead to low intensities. Thus, low intensities should via greater energies correlate with larger spectral indices. Hence it seems to me that one may have to be somewhat cautious in evaluating the background on the basis of the spectra.

2. SMALL-SCALE FIELDS

(*a*) *Evidence from conflicting determinations of field strength*

Next I want to consider the small-scale component of the magnetic field in the galactic disk. Let us for the moment assume that the large-scale component of the magnetic field in the disk, as indicated by the Faraday effects, is of the order of 5×10^{-6} gauss. The problem then arises that the synchrotron radiation from the galactic disk demands a stronger magnetic field. Thus the field would be stronger than its large-scale component and so apparently an important small-scale field should be present. Of course, should it appear in the end that the electron densities have been seriously overestimated and that the Faraday effect gives us a three-times-larger field, there would be no problem with the synchrotron radiation, or with the interstellar optical polarization. Everything would fit very nicely, except that we should have trouble with the *Zeeman-effect* measurements (cf. Verschuur, Paper 66), which certainly tell us that inside the neutral-hydrogen clouds there are no systematic magnetic fields of that magnitude. It has been suggested that the Zeeman effect could then be explained by the assumption that the interstellar clouds would be diamagnetic bubbles in the galactic magnetic field, but when we really put in the numbers we come to a very implausible cloud picture. The pressure in the clouds would have to equal the magnetic pressure $H^2/8\pi$ outside, which leads to very dense and massive clouds of a kind for which we have no evidence. From the theoretical point of view it is also hard to see how the diamagnetic situation could be maintained for a long time, because ambipolar-diffusion processes would tend to mix up the magnetic field and the cloud matter. Eventual instabilities would lead to the same result.

It seems to me that, to reconcile the absence of the 21-cm Zeeman effect and the intensity of the synchrotron radiation from the disk, we indeed have to invoke, in addition to the systematic flux-carrying field, small-scale magnetic fields. As far as the

synchrotron radiation is concerned, there is no difference between a small-scale magnetic field and a large-scale magnetic field. Also, the calculations reported by Greenberg (Paper 65) show that in a small-scale magnetic field with an anisotropy ratio of two in the field-line distribution, the optical polarization is not much less than in a uniform field. The absence of the Zeeman effect is fully compatible with the existence of small-scale fields, because these do not give a net Zeeman effect.

(*b*) *Evidence from depolarization of continuum radiation*

Perhaps the existence of small-scale magnetic fields may also be inferred from the *measurements of depolarization* in the galactic continuum. Van de Hulst mentioned yesterday (see Paper 64, Section 2*e*(*i*), and Van de Hulst 1967, Figure 2) that the polarized component of the galactic continuum radiation has a flatter spectrum than the total radiation. In other words, the degree of polarization decreases strongly with frequency. This can be explained in two ways. (*i*) In a large-scale magnetic field Faraday rotations can mix up the various contributions to the polarized component along the line of sight in such a way that very little net polarization remains. In this case one expects that, on the average, strong depolarizations correlate with large systematic rotations of the plane of polarization. But the polarizations measured by Brouw (Leiden) at different frequencies show that at least in some regions there are only small differences in the orientations of the plane of polarization at 1400 and 600 MHz, while the degree of polarization is significantly smaller at 600 MHz. The simplest way to interpret this is by assuming (*ii*) the presence of small-scale fields which, if the scale is right, depolarize but do not give much systematic Faraday rotation. If the scale is taken very small, the depolarization is ineffective; if it is taken very large, then systematic Faraday rotation over the whole beam is found; so an intermediate scale is required. Quantitatively, it would seem that the data might indicate a field component with a typical scale of the order of 0·1 pc, corresponding to several minutes of arc when seen at a distance of 100 pc. It therefore would appear most interesting to make high-resolution polarization observations in the galactic continuum, in some selected regions at intermediate frequencies (about 800 MHz); the instruments should have a resolution of a few minutes of arc, that is, about a factor of five better than what has been used until now. If small-scale fields are important, a considerable amount of fine structure should appear.

(*c*) *Origin of the small-scale fields*

The origin of the small-scale component of the galactic magnetic field may be related to processes of stellar evolution. Stellar mass loss certainly can lead to the injection of small-scale field components into the interstellar medium. Also, random motions in the interstellar magnetic field will lead to the growth of irregular field components. In the discussion of these processes it is of vital importance to know what the dissipative coefficients for this medium really are, so that one may estimate what scales can be expected after a certain time. At present no good information is available, and it would seem important if the discussions of Petschek's mechanism given by Wentzel (1966, see Paper 21) were extended and confirmed. The small-scale magnetic fields of course also would be very directly relevant to the question of the propagation of cosmic rays in the Galaxy (cf. Papers 61, 71 and 74): they certainly would make cosmic-ray propagation more difficult.

3. DYNAMICAL EFFECTS

Let me finally turn to the dynamical effects associated with the galactic magnetic field. If we believe that the field strength is of the order of 15×10^{-6} gauss, as seems to be implied by the synchrotron observations, we cannot expect strong dynamical effects of the magnetic field on the scale of the Galaxy as a whole. On the other hand, *in individual spiral arms* the magnetic field will be dynamically quite important, and it certainly should ultimately be taken into account also in the theories of spiral structure that have been *en vogue* during this conference. But the idea which was perhaps current in some quarters several years ago (cf. Woltjer 1962), that the magnetic fields might be of dominant dynamical importance, seems by now to be unlikely. The argument in the past has frequently been a process of elimination: one observed certain phenomena, and one investigated what part of the phenomena could be explained; then the unexplained part was taken to show the effects of the magnetic field. It is clear in this case that, the larger one's ignorance, the stronger the magnetic field.

REFERENCES

Berge, G. L., Seielstad, G. A. 1967, *Astrophys, J.*, **148**, 367.
Hoyle, F., Ireland, J. G. 1961, *Mon. Not. R. astr. Soc.*, **122**, 35.
Parker, E. N. 1965, *Astrophys. J.*, **142**, 584.
Setti, G. 1965, *Bull. astr. Inst. Netherl.*, **18**, 51.
Spitzer, L., Tukey, J. 1951, *Astrophys. J.*, **114**, 187.
Van de Hulst, H. C. 1967, *A. Rev. Astr. Astrophys.*, **5**, in press.
Van Woerden, H. 1967, *Bull. astr. Inst. Netherl.*, in preparation.
Wentzel, D. G. 1966, *Astrophys. J.*, **145**, 595.
Woltjer, L. (Ed.) 1962, *Interstellar Matter in Galaxies*, W. A. Benjamin, Inc., New York.

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81. CONCLUDING GENERAL DISCUSSION

M. Schmidt: If all novae became X-ray sources of lifetime 100 years or more, the number of such sources in the Galaxy would be at least 2500, for a nova rate of 25 per year. Since the observed number of sources is much smaller, this suggests that only a small fraction of novae become X-ray sources similar to Sco X–1.

I further have an argument with Burbidge (cf. Paper 74). The following reasoning seems to exclude the strong extragalactic radio sources as origin of cosmic radiation. It is known that strong radio sources are identified with giant elliptical galaxies only. These galaxies have a density of 10^{-4} Mpc^{-3}, or 3×10^{-78} cm^{-3}. If cosmic rays of energy density 10^{-12} erg cm^{-3} originate exclusively in these galaxies, then each galaxy has to supply 3×10^{65} erg or 2×10^{11} $M_{\odot} c^2$, all in cosmic radiation. This can be safely regarded as impossible. I might add that I get the same result as Ginzburg and Syrovatskij (Paper 71); however, my argument does not depend on models of the radio sources, on the synchrotron mechanism, etc.

G. R. Burbidge answers: I have just discussed with Schmidt the arguments he has presented here, and I must agree with him, since his arguments are very similar to those which I used in 1961 to calculate the possible extragalactic cosmic-ray flux. The difference lies in the fact that since then the statistics have changed, because it now appears that not all elliptical galaxies are candidates to become strong radio sources, but only a very small fraction. If this argument is right, then a serious blow is dealt to the hypothesis of extragalactic cosmic-ray origin, and I may have to withdraw some of the remarks I made this morning (Paper 74); i.e., I may be wrong in some of what I have said. I should add however that these arguments, which lead to troubles of their own, associated with the lifetime of the radio galaxies, are dependent on the assumption that a galaxy's optical properties are not changed by the explosive event. I intend to look carefully into this question.

J. E. Baldwin: Woltjer's suggestion (Paper 80, Section *1b(ii)*) that the correlation between low intensity and high spectral index might be due to galactic radiation is indeed a possibility. It would however be surprising to find the observational result (Paper 56, Section 5*b*) that there is a linear relation between temperatures at one frequency and those at another frequency for corresponding points on the sky.

In any case we must make allowance for the known extragalactic radiation derived by counting all radio sources down to the limit of observation. This accounts for some 12 °K at 178 MHz, which is half of that derived for the extragalactic component from the spectral analysis—and of course we do not pretend to have yet counted all the extragalactic radio sources in the Universe!

J. Lequeux: It is tempting to interpret the bend in the radio spectrum of the Galaxy (Paper 56, Figure 5; see also discussion in Paper 74) as due to a change in the predominant energy losses of electrons near 1·5 GeV. If the Galaxy is in a steady state, synchrotron losses are likely to be predominant at $E > 1{\cdot}5$ GeV, and bremsstrahlung losses at $E < 1{\cdot}5$ GeV; one would then expect a change of 0·5 in the spectral index

between low and high frequencies, which is not inconsistent with observations. The bremsstrahlung and synchrotron losses are equal for 1·5 GeV; if the magnetic field is 5×10^{-6} gauss, the mean density of the gas in the region in which the electrons travel is 0·2 cm^{-3}. These figures fit with a model of the Galaxy consisting of a uniform disk of 800 pc thickness, in agreement with Baldwin's deductions (Paper 56, Section 1). The effect of ionization losses is likely to be negligible, except at very low frequencies.

If the bend in the radio spectrum of the Galaxy is indeed as sharp as suggested by Baldwin, the magnetic field has to be fairly constant in the bulk of the emitting regions. This is again consistent with the uniform-disk model deduced from observations.

C. C. Lin: I should like to add a few words to clarify the picture of the magnetic field, according to the density-wave theory of spiral patterns. Woltjer (Paper 80, Section 1*b*) has already explained that the field would be largely circular.

I wish to point out that the field would not undergo further stretching to any significant degree in the long run, although temporary stretching and contraction of the magnetic tubes will take place. To visualize this, consider circular tubes of gas contained in a circular magnetic field. It is easy to see that a stationary state may be reached such that the tube becomes slightly non-circular and rotates around under the influence of a spiral field. The field will increase during part of a cycle and decrease during another part; but a stationary state is maintained in the long run.

The actual field may not be exactly circular to begin with, but if the original deviation is small, the net modification of the ideal situation cannot become large either. There is thus no danger for the magnetic field to increase indefinitely by differential rotation.

H. Alfvén: I have two remarks about Woltjer's talk (Paper 80).

(1) About the possible existence of antimatter he said that, because of the Faraday rotation, no patchy structure of matter and antimatter was possible. This conclusion would be correct if the magnetic field were homogeneous, but since the field is in fact inhomogeneous, it is not convincing. The argument only shows that the patchiness of matter and antimatter must be related to the patchiness of the magnetic field, but this conclusion, I think, one must draw under all conditions: there must be some connection between these two.

(2) With a patchiness of the magnetic field on the scale of 0·1 pc, and a field strength of the order of 10 micro-gauss, particles of energies up to 10^{14} eV will be confined on the lines of force. Therefore, all cosmic radiation below this energy limit could have a certain intensity here and a quite different intensity elsewhere. A magnetic field of this small scale would make it very difficult for cosmic rays to travel in our Galaxy.

S. B. Pikel'ner: I am afraid that Woltjer's model (Paper 80), with a random field of 10^{-5} gauss and a weaker regular field, encounters many major difficulties and can therefore not be accepted. We have no time and I shall only briefly mention my main criticisms.

If the field is random, the magnetic forces correspond to random velocities of about 10 km/sec within the clouds and about 100 km/sec between the clouds. There are no observations of such random motions on a small scale.

The magnetic forces in an elongated random field are not isotropic; they tend to expand the gas perpendicularly to the magnetic field lines and to compress it along the lines.

Thus, the field becomes more isotropic, and there are no forces which can maintain the elongation. Differential rotation is effective in orienting the regular field, but it is ineffective on a small scale.

If the field between clouds is rather random, there should occur a general expansion of rarefied gas, and the thickness of spiral arms should be much larger than is observed even in the continuum radio emission.

A random field with a scale less than 0·3 pc should dissipate very fast, owing to instabilities of various kinds, to Petschek's mechanism of dissipation, and to ambipolar diffusion.

The field cannot be expelled by stars, it is too strong. Moreover, the closed magnetic field lines embedded in a rarefied gas should be pushed out by diamagnetic effects.

I may add that a random field with a scale less than the gyro-radius can not effectively confine cosmic rays, so there should be a considerable deficiency of cosmic rays with $E > 10^{16}$ eV.

The random field cannot help much in the interpretation of observed polarizations. If the rotation measure changed considerably from point to point on a scale smaller than 1 pc, it could explain the depolarization; but this would be in contradiction with the smooth change of polarization plane and rotation measure for neighbouring extra-galactic sources. All these arguments, together with a few more, make me insist on a quasi-regular field model. The Zeeman measurements do not sharply contradict this field model, as the field in the clouds should be a little less than the average field, and we do not definitely know the orientation of field lines in the clouds.

L. Woltjer: I don't want to let Pikel'ner's 10 criticisms go completely unanswered. I certainly would not claim that all through the galactic disk the small-scale magnetic field would have the same preferred direction. All that I would argue is that, when interstellar matter enters a spiral pattern, it is compressed; and when you compress matter that contains an isotropic magnetic field, the field must become anisotropic. Therefore, in the spiral arms where the polarization is produced, I think one would in fact expect that the ellipsoidal field distribution would have its major axis along the arm direction.

J. H. Oort: There is nothing I have to do now but to close this meeting. In doing so I do want to return the thanks of the Organizing Committee, in the first place, to all those who have given such beautiful, clear reviews of the various subjects. We are very grateful for all the work they have spent in preparation; it is only due to them that this conference has been successful. I also wish to thank those who have taken the chairs at the various sessions and who had the difficult problem of keeping within the short time available. It is a pity we could not have more time. Many subjects and many details, although quite important, have remained undiscussed, but I am afraid that is unavoidable, and we shall hope for another conference to start on those. Thank you very much.

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This volume, edited by Professor G. Contopoulos, contains the papers presented at the I.A.U. Symposium on the Theory of Orbits in the Solar System and in Stellar Systems held at Thessaloniki, Greece, 17-22 August, 1964, under the chairmanship of Professor D. Brouwer, Yale University.

The Symposium was concerned with the basic aspect of celestial mechanics, the theory of orbits. The problems discussed range from the fundamental aspects of the three—or *n*-body problem to application of the theory, both in the solar system and in stellar systems, such as clusters or spiral galaxies.

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1966, 398 pp., 120s.

This volume, edited by Dr Hans Hubenet, contains the papers presented at the I.A.U. Symposium on Abundance Determinations in Stellar Spectra held at Utrecht University, 10-14 August, 1965, and presided over by Professor C. de Jager, Utrecht University.

The main purpose of this Symposium was to present a critical evaluation of the difficult and important problems involved in the determination of the element abundances in stars and other celestial bodies. With the large variety of problems treated, the volume provides an authoritative reference work of value to nuclear physicists, space scientists and astrophysicists.

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